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RESEARCH REPORT 1 - 70

BREATHING IMPEDANCE OF THE MARK VIII AND MARK XI SEMI-CLOSED UNDERWATER BREATHING APPARATUS

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BACKGROUND

A diver breathing with underwater breathing apparatus will have his ventilatory capability degraded by an inherent breathing impedance in the equipment used. The impedance of both the equipment and the diver's respiratory system will increase as ambient pressure increases. Although breathing impedance in diving equipment has been of concern to physicians, physiologists, and engineers for several decades, there is little information concerning the deleterious physiological effects imposed on the diver breathing with SCUBA. Moreover, there is a paucity of information which delineates bioengineering specifications for breathing resistance in underwater breathing apparatus.

Operationally, such information is extremely important because the increased work of breathing with SCUBA causes a degradation in the diver's capacity for physical exertion. Moreover, in resistive breathing, there is a concommitant retention of carbon dioxide. This latter factor is of considerable significance due to the marked potentiating effects of carbon dioxide on inert gas narcosis and susceptibility to oxygen toxicity.

Previous difficulties in the study of breathing impedance of underwater breathing equipment stem from several areas. It is technically difficult to measure pressure differentials and flow rates in submerged underwater breathing apparatus. Secondly, it is technically difficult to measure the physiological changes in the diver who is breathing with an underwater breathing apparatus while submerged. Because of these difficulties, previous assessments of the acceptability of breathing resistance in underwater breathing apparatus have been based on the subjective impressions of divers using the equipment. However, this method of evaluation provides information of dubious value, as divers often have a cavalier "can do" attitude towards their diving equipment and are willing to tolerate a high level of discomfort.

The Submarine Development Group One Medical Department conducted an extensive study to measure the breathing resistance encountered by an exercising subject breathing with the Mark VIII, Mod I and the Mark XI, Mod O semi-closed underwater breathing apparatus. The objectives of this study were: a) The delineation of physiological effects imposed by equipment resistance in the presence of gases of normal and increased density; b) The development of techniques to evaluate breathing resistance in diving equipment; c) The tentative establishment of specifications for engineering design of diving equipment in terms of breathing resistance.

The scope of this study is limited though in that it only addresses the diver and his equipment in the "dry" state. Immersion causes profound physiological changes in man, and alters to an undetermined degree the respiratory impedance of both man and his underwater breathing equipment. Subsequent study should be directed to other types of underwater breathing equipment and to developing the technology to study the submerged diver and his equipment.

It is not the purview of this report to provide an extensive treatise examining all the factors that increase a submerged diver's respiratory impedance. However, a brief review of the physiological effects of pressure breathing and of resistive breathing is presented so that the background for later discussion can better be understood.

When a diver breathes with underwater breathing equipment in the water, a number of factors interact to increase the diver's respiratory impedance. The first major factor that increases a SCUBA diver's work of breathing is posed by the resistance to gas flow of the components of his breathing apparatus and the compliance of his breathing bags. This group of factors will be affected by alterations in gas density and in ambient temperature. The second major factor that increases respiratory impedance results from imbalances of hydrostatic pressure acting upon the interconnected diver's lungs and the breathing bags of his underwater breathing apparatus.

HYDROSTATIC EFFECTS

With most diving equipment a SCUBA diver will be positive or negative pressure breathing to a significant degree most of the time that he is in the water. A recent study of the breathing hydrostatic of bag type apparatuses has examined in detail the interrelationships of the lung centroid, head centroid, the bag collapse plane and the exhaust valve location and setting, all of which interact to regulate the degree of positive or negative pressure breathing which a diver will encounter (46). This analysis shows that a diver using the Mark VIII, Mod 0, semi-closed underwater breathing apparatus with the exhaust valve 1/3 closed (giving an intrabag pressure of + 15 cm H_2O) will be positive pressure breathing a pressure greater than + 5 cm H_2O in over 70% of the possible positions that he can assume in the water. In some positions with this exhaust valve setting, the diver may be positive pressure breathing at pressures as great as + 45 cm H_2O. In 20% of the possible positions the diver can assume, he will be negative pressure breathing at pressures more negative than - 5 cm H_2O.

The positions that a diver most commonly employs are the upright (vertical) and prone (swimming) positions. In the upright position, a diver using the Mark VIII with the same exhaust valve setting will be negative pressure breathing at - 10 cm H_2O. In the prone position, the diver will be positive pressure breathing at + 15 cm H_2O.

The design characteristics of the Mark XI UBA tend to reduce the hydrostatic imbalances encountered by the diver, especially the magnitude of positive pressure breathing. However, even with this equipment, the diver can still experience hydrostatic pressure imbalances up to + 25 cm H_2O in some positions

The physiological effects of both positive and negative pressure breathing have been extensively investigated. However, these studies have only examined the resting individual and not man at work. As a consequence, the validity of application to the present study and to the working diver is limited.

POSITIVE PRESSURE BREATHING

In aviation positive pressure breathing of 100% oxygen is used to improve aviator oxygenation at high altitude. As a consequence, the physiological consequences of positive pressure breathing have been extensively studied and reviewed.

Subjectively, the sensation of positive pressure breathing is considered preferable to that of negative pressure breathing (50). Positive pressure breathing with a mouthpiece at pressures around + 25 cm of H_2O is very uncomfortable; above this level it cannot be tolerated for very long (21). At these pressures the lips cannot be held against the mouthpiece and gas is lost through gaps between the mouthpiece and lips. The cheeks and neck are distended and there may be considerable discomfort associated with this distention.

Effects Upon Lung Volumes and Pulmonary Ventilation

Positive pressure breathing is accompanied by a progressive distention of the lung. Vital capacity and residual volume are increased during positive pressure breathing. Expiratory reserve volume is increased 33% at a pressure of + 5 cm H_2O and 60% at + 10 cm H_2O (21).

There is little change in respiratory dead space during positive pressure breathing at rest with pressures up to + 10 cm H_2O. At pressures greater than + 10 cm H_2O, both anatomical and physiological dead space increases markedly (21).

This increase in physiological dead space is though to result from decreased perfusion of alveoli with blood which accompanies the reduction in cardiac output and fall in pulmonary artery pressure during positive pressure breathing.

As respiratory dead space is increased during positive pressure breathing, total pulmonary ventilation increases to maintain the same alveolar ventilation. As a consequence, during positive pressure breathing there is often a small degree of hyperventilation (21). This increased respiratory minute volume is effected primarily through an increase in tidal volume and to a lesser degree by increases in respiratory frequency.

Effects Upon Mechanics of Breathing

Inspiratory flow rates are increased with pressure breathing and the time required for inspiration is lessened. Mean expiratory flow rates fall slightly with positive pressure breathing and there is a flattening of the expiratory flow pattern.

During positive pressure breathing there is increased tone of expiratory musculature. During positive pressure breathing at pressures greater than + 10 cm H_2O, inspiration occurs by relaxation of the expiratory musculature. At pressures above + 20 cm H_2O, expiratory muscle tone is markedly increased in order to prevent overdistention and discomfort of the lungs.

Pulmonary compliance appears to be unaffected by small amounts of positive pressure breathing (21) but at high lung volumes it is decreased. Positive pressure breathing causes a reduction in airway resistance, the degree of which appears to be directly related to the degree of positive pressure breathing (21). This change in airway resistance is thought to be primarily a result of the increased airway diameter caused by distention of the lungs. A secondary mechanism which may be responsible for this phenomenon may be a decrease in the vascularity of the bronchial mucosa which is tending to increase airway resistance.

Effect on Metabolism and Work of Breathing

Positive pressure breathing during rest at pressures of + 40 cm H_2O has been shown to cause an increase in oxygen consumption and carbon dioxide production. Increased work of breathing most likely accounts for these increases. During positive pressure breathing, there is evidence for the impairment of nervous coordination of respiratory musculature which would tend to lessen the efficiency of the respiratory muscles (21). Secondly, while inspiratory work may be decreased, during positive pressure breathing at low pressures, there will be an increase in the work required for expiration. At higher pressures, inspiratory work may become significant as the respiratory musculature limits the degree of distention during inspiration.

Cardiovascular Effects

A primary effect of positive pressure breathing is the displacement of blood from the thorax into the limbs. As intrapulmonary pressure increases, it reflexly produces a peripheral arterial and venous vasoconstriction. Concomitently there is a tachycardia and increases in arterial and central venous blood pressure. Positive pressure breathing at 30 cm H_2O reduces cardiac output about 15%. At + 40 cm by H_2O cardiac output is reduced about 30% (21). At pressures of 20 cm H_2O or above, syncopal episodes may occur which are thought to result from the marked reduction in effective blood volume (32). Investigators have noted that concurrent hypoxia, hypocapnia or anxiety will potentiate the occurrence of positive pressure breathing syncope.

NEGATIVE PRESSURE BREATHING

Paton and Sand (50) reported that positive pressure breathing with expiratory difficulty was subjectively preferable to the sensation of negative pressure breathing (NPB) with inspiratory difficulty. During negative pressure breathing there may be pain in the lower chest and throat. Instances of pulmonary edema have been reported in divers who have been negative pressure breathing at high pressures.

Effect on Lung Volumes and Pulmonary Ventilation

During negative pressure breathing at 20 cm H_2O, vital capacity is decreased about 15% (62). Paton and Sand (50) and other investigators (60) have found that vertical immersion in water, even though the subject is concurrently positive pressure breathing, causes a decrease in vital capacity. Tidal volume diminishes during negative pressure breathing, and expiratory reserve volume progressively decreases with increasingly negative pressures.

Paton and Sand reported that the respiratory minute volume of two subjects who were negative pressure breathing during both rest and exercise was unchanged from control values (50). The composition of alveolar gas during negative pressure breathing has not been studied.

Effect on Mechanics of Breathing

During moderate degrees of negative pressure breathing, Paton and Sand (50) reported that inspiratory and expiratory flow rates remain unchanged. Other investigators have found marked increases in peak respiratory flow rates during NPB (63). Decreases in pulmonary compliance have been reported during NPB (8-A), which have been attributed to engorgement of the lungs with blood. Ting et. al (63) questioned the validity of this finding because of the artifact introduced into esophageal balloon measurements at small lung volumes. Subsequent investigation (64) indicates that compliance is decreased during NPB and that a primary contribution to this phenomenon may be the closure of alveoli (64).

Airway resistance is markedly increased by vertical immersion and by negative pressure breathing. During vertical immersion to the level of the neck, airway resistance is increased about 60% (2). During negative pressure breathing at 20 cm H_2O, airway resistance increases 160% (2). The increase in airway resistance which occurs with immersion is attributed to the decreased airway diameter which occurs at low lung volumes. The further increase found during negative pressure breathing is thought to result from compression of extrathoracic airways.

Hong, et. al. (33) have found that immersion to the level of the neck produces an almost twofold increase in total work of breathing. Seventy-five percent of this increase was attributable to an increase in elastic work, and the remainder to increased dynamic work. This marked increase in dynamic work can be attributed to an increase in the flow resistance of airways functioning at small lung volumes.

Effects Upon Metabolism and Work on Breathing

Paton and Sand (50) studied the metabolism of subjects at rest and during exercise who were negative pressure breathing. Neither oxygen consumption nor carbon dioxide production were found to change from control values. These investigators concluded that negative pressure breathing did not significantly increase work of breathing. However, this conclusion is suspect as Paton and Sand's observations were small both in number and in level of exercise. Possibly a more careful and larger number of experiments would demonstrate changes in oxygen consumption resulting from increased work of breathing.

Cardiovascular Effects

During NPB at pressure of - 30 cm H_2O, pulse rate is increased, arterial blood pressure is only slightly affected and central venous pressure is reduced (63). During negative pressure breathing the veins entering the thoracic cavity collapse and the thoracic circulation operates at a considerably reduced pressure. The pressure differential between these two circulations is thus maintained by the left ventricle.

STANDARDS FOR POSITIVE AND NEGATIVE PRESSURE BREATHING

Because of the syncope and deleterious physiological effects which positive pressure breathing can cause, continuous positive pressure breathing at altitude (without use of a pressure suit or jerkin) is limited to a maximum pressure of + 20 cm H_2O (21). Maximum permissible limits for intermittent positive pressure breathing have not been proposed.

The maximum negative pressure at which man can safely breath for long periods has not been established. There is general agreement that negative pressure breathing is more hazardous than positive pressure breathing. It is only reasonable to limit negative pressure breathing to a maximum pressure of - 20 cm H_2O.

RESISTIVE BREATHING

Any system of tubing, connections, check valves, etc., imposes a certain amount of opposition to the passage of gas. In underwater breathing equipment, sources of flow resistance fall into two overlapping categories. The first category is the restriction to flow in the form of inadequate diameter of tubing, check valves, etc., which will not accommodate the respiratory air flow of a working man. The second contributor to air flow resistance is any source of turbulence such as projecting obstructions, check valves, etc., which cause radical redirection of flow.

Semi-closed underwater breathing apparatus always have a rubber counterlung or re-breathing bags to act as reservoirs for gases. Additional respiratory impedance is imposed by the elastic pressure under which the gases are held in the bags. Bag elastic pressure depends upon the compliance of the bag and the volume of gas contained in the bag. The volume of gas in the bag depends upon the rate of injection of fresh gas and on the characteristics of the exhaust valve through which excess gas is voided to the surrounding water.

Cooper attempted to quantitate the amount of work done against elastic forces and the amount of work done against frictional forces in breathing equipment (19). He found that at high respiratory minute volumes, the amount of work done against elastic resistance was very small. With diving equipment it is conceivable that cold water may alter the compliance of breathing bags so that elastic resistance becomes a significant contributor to the work required to breath with UBA.

Numerous studies have investigated the physiological effects of breathing against added external resistance. Comparison of the findings of one study with those of another is often difficult because of the dissimilar experimental techniques and types of subjects employed in these studies.

Many past studies have been concerned with determining the physiological cost involved in using respiratory protective devices such as gas masks and devices to filter and absorb particulate matter from the atmosphere. The breathing resistance characteristics of these devices may markedly differ from those present in underwater breathing apparatus.

Subjectively, increased inspiratory resistance has been reported to be less objectionable than increased expiratory resistance. Except when resistive loads are minimal, Silverman recommended that expiratory resistance should never exceed more than 40% of the total imposed resistive load (57). When the degree of respiratory obstruction becomes too great for a given ventilation, the subject experiences a sensation of choking dyspnea (3). This point at which resistance becomes intolerable is probably signalled by a combination of anoxemia and hypercapnia.

Effect on Lung Volumes and Pulmonary Ventilation

Adding resistance to inspiration and expiration prolongs the time required for each phase of respiration (13, 66). The greater the amount of resistance, the greater the degree of prolongation. However, the expiratory phase of respiration is considerably more affected than inspiration, and with high resistances is markedly lengthened.

Added resistance to expiration (66) and the combination of added inspiratory and expiratory resistance (13) produces an increase in expiratory reserve volume. It is believed that the increase in expiratory reserve volume that occurs when resistance to expiration is increased is related to the prolongation in the time of expiration. Without added resistance the elasticity of the lung is normally sufficient to pull the thoracic cage back to the resting expiratory level. With added resistance and the prolongation of expiration, there may be insufficient time for the chest to regain its resting position before the respiratory center signals for the next inspiration.

Adding resistance to inspiration and expiration separately or in combination causes a decrease in respiratory minute volume (13, 57). The combination of added resistance to inspiration and expiration simultaneously causes the most marked decrease in ventilation. The greater the amount of imposed resistance to any phase or phases of respiration, the more profound the degree of hypoventilation. This phenomenon is seen in subjects both at rest and during exercise.

As resistance to breathing is progressively increased, there is a progressive decrease in respiratory frequency and often an increase in tidal volume (13, 57). This alteration in breathing pattern may be a mechanism which the subject intuitively employes to minimize work of breathing. Otis (48) has theoretically predicted that when flow resistance is increased, the optimal respiratory frequency falls in order to minimize energy expenditure.

As a result of the hypoventilation that occurs with resistive breathing, alveolar carbon dioxide tension rises and alveolar oxygen tension falls (13, 66). Cain and Otis (13) suggest that retention of carbon dioxide during resistance breathing indicates a compromise in which CO_2 tension is allowed to remain elevated so that additional energy is not expended to reduce it to the original pre-resistance level. This explanation is consistent with Cherniack's observation of a decreased sensitivity to carbon dioxide in normal subject's breathing against artificial obstruction (17).

The effects of increased breathing resistance upon respiratory dead space have not been studied. Physiological dead space most likely progressively increases as the amount of external resistance to breathing is increased. The marked prolongation of expiration, which occurs during resistive breathing and which increases expiratory reserve volume, would also increase and prolong the positivity of intrathoracic pressure and reduce pulmonary circulation. The net effect of the resulting alteration in $\dot{V}_a/\dot{Q}$ would be to increase physiological dead space.

Effect on Mechanics of Breathing

As resistance is added to the flow of gas during respiration, an increased inspiratory and expiratory effort is required to maintain adequate ventilation. When added resistance is imposed on both the inspiratory and expiratory phases of respiration, inspiratory work is consistently larger than expiratory work (13). The inspiratory phase of respiration is always shorter than the expiratory phase. As such, the inspiratory muscles generate a higher flow rate and higher pressure than the expiratory muscles. This phenomenon accounts for the additional work during inspiration.

Expiratory work per breath also tends to be greater when resistance is added to both the inspiratory and expiratory phases of respiration, than to expiration alone (66). Since the increases in tidal volume are generally quantitatively the same in both situations, the difference in expiratory work is thought to be due to the greater expiratory flow and hence pressure that occurs when both inspiration and expiration encounter resistance (66).

Effect on Metabolism and Work of Breathing

Cain and Otis (13) reported an increase in the oxygen consumption of resting subjects respiring against added resistance to inspiration, to expiration and the combination. Silverman found that the oxygen consumption of subjects was slightly increased if they were breathing against added inspiratory resistance or breathing against a combination of added inspiratory and expiratory resistance at light work loads (57, 58). At heavy work loads, breathing against expiratory resistance alone, and respiring against combined inspiratory and expiratory resistance caused an appreciable decrease in oxygen consumption. In this latter situation, respiratory exchange quotients were often greater than 1.0. Findings similar to those of Silverman have been reported by Tabakin (59) and by Burton (11). In a careful study of the oxygen cost of breathing, McKerrow and Otis (43) found a decrease in the oxygen consumption and ventilation of subjects breathing against a combination of increased inspiratory and expiratory resistance.

Thompson, et. al (61) studied the recovery oxygen consumption of subjects after they had been breathing against increased external resistance. These investigators found that there was a positive correlation between resistance and an elevated recovery oxygen uptake after the performance of moderate work. This increase in recovery oxygen consumption was attributed to the "pay-back" of an oxygen debt contracted during resistive breathing.

A recent study by Cerretelli, et. al. (16) examined the oxygen consumption of subjects breathing through graded resistances during exercise. These investigators found that the maximum oxygen uptake was reduced by the addition of resistance, but that the relationship between oxygen uptake and work load was unchanged. On this basis they concluded that there was no indication that resistance breathing caused a shift to an anaerobic type of metabolism.

From the foregoing discussion, it is obvious that there is considerable controversy with regard to the effect of resistance breathing upon oxygen consumption. Much of the confusion probably results from differences in experimental methodology. Moreover, it is apparent that the additional metabolic requirements encountered during resistance breathing are not clearly reflected in the parameter of oxygen consumption.

Cardiovascular Effects

Small increases in pulse rate have been reported in subjects who are breathing against added external resistance both at rest and during exercise (11, 58). Cain and Otis found that the cardiac output of subjects who were resistance breathing was diminished during expiration, but increased during inspiration (13). The overall effect of this phenomenon was to reduce cardiac minute volume.

STANDARDS OF RESISTANCE FOR BREATHING APPARATUS

Silverman, et. al. (57) conducted the most extensive studies of the physiological effects of resistive breathing. These investigators referred to resistances that they used as 82/53, etc. This designation implied that the subjects breathed against a resistance such that a constant flow of 85 L/min required a force of 82 mm H_2O on the inspiratory side and 53 mm H_2O on the expiratory side.

The physiological effects and subjective sensations of Silverman's subjects indicated that 15 minutes of exercise at a work load of 830 Kg-M/min while breathing against at 82/53 resistive force was poorly tolerated but could be done. At a work load of 1107 Kg-M/min, the maximum tolerable resistance was noted to be 64 mm H_2O on the inspiratory side and 41 mm H_2O on the expiratory side. These investigators measured the total external respiratory work done in these situations, and recommended that the rate of external respiratory work should not exceed 0.6% of the total rate of body work. The recommendation of Hart (29) for maximum allowable resistance agrees with the standard proposed by Silverman. Cooper (19) re-evaluated Silverman's work, and on the basis of this re-appraisal and his own work, decided that external respiratory work should not exceed 0.74% of the total rate of body work.

One difficulty in defining the acceptable limits for breathing resistance is that subjects trained in breathing against added resistance have a greater tolerance of discomfort and superior physiological adaptation (19, 57). By modifying his respiratory frequency, shape of gas flow curves and possibly gas exchange values, the trained subject is able to reduce his respiratory work rate. However, as a breathing apparatus is likely to be used by individuals with varying levels of experience in resistance breathing, the permissible level of breathing resistance must be attuned to the requirements of the untrained man.

Lanphier proposed semi-quantitative standards for acceptable breathing resistance in SCUBA (51). He stated that, "At moderate work rates, the average diver is reasonably comforable for considerable periods if the inspiratory and expiratory pressures do not exceed 10 - 15 cm at peak flow. Subjects usually report definite discomfort when the pressures rise much above 20 cm H_2O." These criteria have been used by the U. S. Navy Experimental Diving Unit for determining the accepability of breathing resistance in SCUBA (34).

A comparison of the standards proposed by Lanphier with those of Silverman (57) and Cooper (19) can tentatively be made. In making this comparison, the following assumptions were made: Lanphier's divers were working at an external work load of 600 Kg-M/min; respiratory minute volume was 30 L/min and respiratory frequency 15 breaths/min; the shape of the respiratory wave had a sine wave configuration (51). Using these assumptions, peak pressures of 10 cm H_2O would represent an external respiratory work rate equivalent to 0.6% of the external work load. Lanphier reported that in general his divers were able to tolerate greater amounts of equipment resistance than were Silverman's subjects. The fact that Lanphier's subjects were divers, experienced in breathing against external resistance, probably accounts for this difference in degree of tolerance.

METHODS and MATERIALS

EXPERIMENTAL DESIGN

The basic feature of this experiment was the study of physiologic parameters in subjects who were at rest or exercising while breathing normal or increased density gas mixtures through a low resistance breathing system, with the MARK VIII, Mod 1 Underwater Breathing Apparatus and with the MARK XI, Mod 0 Underwater Breathing Apparatus. Additionally, the differential pressures generated in various components of the MARK VIII and MARK XI semi-closed underwater breathing apparatus were measured while the equipment was being used.

The conditions of physical activity studied were rest, moderate work (500 Kg-M/min) and heavy work (1000 Kg-M/min). The breathing gases used both during rest and exercise with each breathing system were 30% oxygen - balance nitrogen and 30% oxygen - balance sulfur hexafluoride.

Table 1 gives the densities for the gases used in this study. Table 2 shows the density of a mixture of one atmosphere of oxygen, balance helium at pressures equivalent to 500, 600, and 700 feet of sea water. Comparison of the relative densities between Tables 1 and 2 shows that a 30% oxygen, balance sulfur hexafluoride mixture at sea level pressure is as dense as a one atmosphere oxygen, balance helium mixture at a depth equivalent to 600 to 700 feet of sea water.

TABLE 1

List of densities for gases discussed in text at 70°F and 1 atmosphere Absolute Pressure (41, 65)

Gas	gm/liter
He	0.1656
N_2	1.161
O_2	1.326
SF_6	6.139
AIR	1.205
O_2, 30% N_2, 70%	1.211
O_2, 30% SF_6, 70%	4.695

TABLE 2

Density of 1 atmosphere of O_2, balance helium mixture at 70°F and pressures equivalent to 500, 600, and 700 feet of sea water(41,

Depth (FSW)	gm/liter
500	3.835
600	4.337
700	4.839

SUBJECT SELECTION and TRAINING

The physical data and diving experience of the six normal male subjects employed in this study are given in Table 3. All were in good physical condition. Four of the subjects were experienced divers; two had no diving experience.

Each subject was intensively trained prior to the days of experimentation. This training period was designed to put the subject at ease in the experimental situation and teach him to pedal a bicycle ergometer in time with a metronome.

Ages, Body Measurements, Pulmonary Functions, and Diving Experience of Subjects.
TABLE 3

Subject	Age	Wt Kg	Height cm	BSA M^2	Forced Vital Capacity Liters BTPS	Fev 1.0 %	MVV L/Min BTPS	Diving Experience No. of Years	Equipment Studied
E.B.	35	68.0	172.1	1.81	4.94	81.7	161.2	10	Low Resistance Mark VIII Mark XI
B.D.	20	61.2	170.2	1.75	4.70	86.1	128	0	Low Resistance Mark VIII Mark XI
R.L.	22	63.0	170.2	1.73	5.10	85.9	146.5	0	Low Resistance Mark VIII
W.L.	30	82.5	176.5	2.00	5.20	89	157	13	Low Resistance Mark VIII Mark XI
C.T.	48	87.1	182.9	2.05	5.79	87	161.2	22	Low Resistance Mark VIII
R.V.	33	61.2	167.6	1.68	4.00	84.7	134	10	Low Resistance Mark VIII

EQUIPMENT

Exercise

Work was performed by the subject who pedaled a Collins Electronic Ergometer at a constant rate in time with a metronome. Ambient temperature was maintained at 72 - 77°F.

A. LOW RESISTANCE SYSTEM

The general experimental arrangement of the Low Resistance System is shown in Figure 1.

GAS ADMINISTRATION, BREATHING APPARATUSES AND VENTILATION MEASUREMENTS

The composition of the gas mixtures used in this part of the study were: 30% oxygen-balance Nitrogen and 30% oxygen - balance sulfur hexafluoride. Each compressed gas mixture was reduced and bled into a large balloon reservoir. A modified Otis-McKerrow exercise valve was used for the administration of the breathing mixture.

A Fleisch pneumotachometer which had been calibrated for 70% nitrogen, 30% oxygen and 70% sulfur hexafluoride, 30% oxygen mixture (nominal flow rate 360 L/Min - max flow rate 450 L/Min) was affixed to the breathing valve. The dead space of this arrangement was 140 cc. The pneumotachometer screen was heated to prevent condensation of water vapor from altering the flow characteristics of the pneumotachometer screen.

The differential pressure drop across the pneumotachometer screen during respiration was measured with a Hewlett-Packard 270 differential gas pressure transducer and flow recorded on an oscillographic recorder. The output from the flow carrier preamplifier was fed into an integrating preamplifier to obtain volume which was recorded on another channel of the recorder.

A Hewlett-Packard 267-BC differential strain gauge measured the difference between mouthpiece and esophageal pressures. Another differential strain gauge measured the differential pressure between the mouthpiece and ambient. The outputs of these two strain gauges were recorded on the oscillograph.

Pleural pressure was measured with latex balloons 9.5 cm long with a circumference of 3.5 cm. The balloons were fitted over a polyethylene catheter with 1.3 mm internal diameter. The balloons were positioned in the esophagus as recommended by Milic-Emili et. al. (44). The balloons were then filled with helium and the volume adjusted to 0.4 cc. The correct balloon position was ascertained in each subject before the initial experiment and balloon position was kept constant during experiments.

GAS ANALYSIS

Expired gas was directed by means of 1-1/2" ID smooth bore rubber tubing to a 10 liter mixing chamber. Mixed expired oxygen and carbon dioxide were continuously sampled from the mixing chamber. Gas sample flow rate was maintained at 150 ml/min.

Oxygen

The oxygen content of the mixed expired gas was measured with a Beckman Model - C (0-50% range) paramagnetic oxygen analyzer. Oxygen concentration readings were noted every 20 - 30 seconds.

When sulfur hexafluoride was present in the gas being analyzed, the following correction factor was used in order to obtain the correct concentration of oxygen:

$$\frac{\text{CORRECT OXYGEN \%} = (O_2\text{\% READING} + 1.633)\ (100)}{101.633} \qquad (6)$$

Carbon Dioxide

The carbon dioxide concentration of the mixed expired gas was measured with a Godart Capnograph whose output was read out on an oscillographic recorder. The presence of sulfur hexafluoride was found not to interfere with the measurement of carbon dioxide concentration by the Capnograph. Additionally, to minimize any effect with sulfur hexafluoride might have upon CO_2 analysis, the Capnograph was calibrated with carbon dioxide mixtures in a sulfur hexafluoride, oxygen background when sulfur hexafluoride was present in the breathing gas.

Alveolar Carbon Dioxide

A sample line was connected to the subject's mouthpiece. When alveolar carbon dioxide was to be measured, this line was opened and connected to the sample head of the CO_2 analyzer. The mouthpiece gas was continuously sampled for a period of 10 to 12 breaths. Alveolar carbon dioxide tension was ascertained by measuring the percentage of carbon dioxide after four-fifths of the time of expiration, a technique suggested by Rahn and Farhi (52).

PULSE RATE

Electrodes were affixed to the subject's precordial region and heart rate was continuously monitored with a Hewlett-Packard high gain preamplifier and recorded on an oscillograph.

B. HIGH RESISTANCE SYSTEMS

GAS ADMINISTRATION, BREATHING APPARATUSES AND VENTILATION MEASUREMENTS

The compositions of the gas mixtures used in this phase of the study were: 40% oxygen - balance nitrogen and 40% oxygen - balance sulfur hexafluoride. Each compressed gas mixture was reduced and injected at a constant rate into the inhalation side of underwater breathing apparatus being evaluated. Injection rates were adjusted for each activity level so that the inspired oxygen concentration was maintained between 27 to 33%. The exhalation bag exhaust valve was then set to relieve when exhalation bag pressures reached 5 to 6 cm H_2O.

Two types of underwater breathing apparatus were evaluated in this study: the MARK VIII, Mod 1 UBA and the MARK XI, Mod 0 UBA. The MARK VIII underwater breathing apparatus was studied in conjunction with the MARK VI mouthpiece unit. Figure 3 depicts the breathing circuit of the MARK VIII UBA; Figure 4 shows the MARK VI mouthpiece unit. The internal diameter of the hoses and check valve orifices of this unit are 7/8".

The MARK XI, Mod O UBA was evaluated with both the MARK VI mouthpiece unit and a specially fabricated mouthpiece assembly which incorporated the check valves, connectors and hoses from the modified Kirby-Morgan Clamshell helmet. A large bore exercise mouthpiece was used in conjunction with the Kirby-Morgan unit. Figure 5 shows the breathing circuit of the MARK XI UBA and Figure 6 demonstrates the Kirby-Morgan mouthpiece assembly. The Kirby-Morgan Clamshell helmet components differ princiapally from those in the MARK VI mouthpiece unit in that the internal diameter of the hoses and check valve orifices are 1-1/2", the check valves themselves are larger and made of a more pliant material, and acute turns of the passages which cause radical redirection of flow have been eliminated.

To ensure that the incorporation of the Kirby-Morgan Clamshell helmet components into a mouthpiece assembly did not appreciably increase the flow resistance, inhalation and exhalation flow resistance was determined with N_2-O_2. Figure 7 shows the inhalation flow resistance of the Kirby-Morgan helmet and the component mouthpiece assembly. Figure 8 depicts the exhalation flow resistance of these two arrangements. The slight increase in flow resistance caused by the modification was not considered to be significant.

The same Fleisch pneumotachometer that was used in the low resistance phase of the study was incorporated into either the MARK VI mouthpiece unit or into the mouthpiece assembly fabricated from Kirby-Morgan components. The pneumotachometer screen was heated as previously described. The total dead space of the MARK VI mouthpiece unit with the pneumotachometer was 147 cc, that of the Kirby-Morgan component mouthpiece with pneumotachometer was 150 cc.

Recordings of flow and volume were obtained as in the low resistance phase of the study. Mouthpiece to ambient and esophageal to mouthpiece differential pressures were measured and recorded as previously described. Additionally, differential pressure measurements were made at several sites of the Underwater Breathing Apparatus. These differential pressures were measured with Hewlett-Packard 267-BC differential pressure transducers, each of whose output was amplified by a carrier preamplifier and recorded on an oscillograph. The sites of the differential pressures monitored in the MARK VIII and the MARK XI Underwater Breathing Apparatus were:

a. Inhalation bag ambient differential pressure

b. Exhalation bag to ambient differential pressure

c. Differential pressure from the inlet side of the carbon dioxide absorbent cannister to the outlet side.

GAS ANALYSIS

Oxygen and Carbon Dioxide

During the measurement periods gas was allowed to bleed from the inhalation and exhalation bags into 5 liter gas sample bags from which all gas had previously been evacuated. The flow rate of gas into each bag was regulated at 200 - 250 cc/min. These gas samples were then analyzed in triplicate for oxygen and carbon dioxide by the Micro-Scholander technique (56).

Alveolar Carbon Dioxide

Measurements of Alveolar Carbon Dioxide were made by the same technique employed in the low resistance phase of the study.

PULSE RATE

Heart rate was monitored by the same method described in the low resistance phase of the study.

EXPERIMENTAL PROCEDURE

Conditions Studied

This study was concerned only with the steady-state phase of exercise, and all the data and calculations reported pertain only to steady-state conditions. Measurements of the physiological parameters of ventilation, metabolism, and cardiovascular response (together with equipment response measurements when appropriate) were obtained on 6 subjects during each of the following conditions:

1 At rest, breathing 30% oxygen - 70% nitrogen through a low resistance breathing system.

2. At rest, breathing 30% oxygen - 70% sulfur hexafluoride through a low resistance breathing system.

3. At rest, breathing 30% oxygen - balance nitrogen through the MARK VIII UBA.

4. At rest, breathing 30% oxygen - balance sulfur hexafluoride through the MARK VIII UBA.

5. Exercising at a work load of 500 Kg-M/Min., breathing 30% oxygen, 70% nitrogen through a low resistance breathing system.

6. Exercising at a work load of 500 Kg-M/Min., breathing 30% oxygen - 70% sulfur hexafluoride through a low resistance breathing system.

7. Exercising at a work load of 500 Kg-M/Min., breathing 30% oxygen - balance nitrogen through the MARK VIII UBA.

8. Exercising at a work load of 500 Kg-M/Min., breathing 30% oxygen - balance sulfur hexafluoride through the MARK VIII UBA.

9. Exercising at a work load of 1000 Kg-M/Min., breathing 30% oxygen - 70% nitrogen through a low resistance breathing system.

10. Exercising at a work load of 1000 Kg-M/Min., breathing 30% oxygen - 70% sulfur hexafluoride through a low resistance breathing system.

11. Exercising at a work load of 1000 Kg-M/Min., breathing 30% oxygen - balance nitrogen through the MARK VIII UBA.

12. Exercising at a work load of 1000 Kg-M/Min., breathing 30% oxygen - balance sulfur hexafluoride through the MARK VIII UBA.

Measurements of the physiological parameters of ventilation, metabolism, and cardiovascular response together with equipment parameters were obtained on 3 subjects during each of the following conditions:

1. At rest, breathing 30% oxygen - balance nitrogen through the MARK XI UBA with the MARK VI mouthpiece unit.

2. At rest, breathing 30% oxygen - 70% sulfur hexafluoride through the MARK XI UBA with the MARK VI mouthpiece unit.

3. At rest, breathing 30% oxygen - 70% nitrogen through the MARK XI UBA with the Kirby-Morgan component mouthpiece assembly.

4. At rest, breathing 30% oxygen - balance sulfur hexafluoride through the MARK XI UBA with the Kirby-Morgan component mouthpiece assembly.

5. Exercising at a work load of 500 Kg-M/Min., breathing 30% oxygen - 70% nitrogen through the MARK XI UBA with the MARK VI mouthpiece unit.

6. Exercising at a work load of 500 Kg-M/Min., breathing 30% oxygen - 70% sulfur hexafluoride through the MARK XI UBA with the MARK VI mouthpiece assembly.

7. Exercising at a work load of 500 Kg-M/Min., breathing 30% oxygen - balance nitrogen through the MARK XI UBA with the Kirby-Morgan component mouthpiece assembly.

8. Exercising at a work load of 500 Kg-M/Min., breathing 30% oxygen - 70 % sulfur hexafluoride through the MARK XI UBA with the Kirby-Morgan component mouthpiece unit.

9. Exercising at a work load of 1000 Kg-M/Min., breathing 30% oxygen - balance nitrogen through the MARK VI mouthpiece unit.

10. Exercising at a work load of 1000 Kg-M/Min., breathing 30% oxygen - 70% sulfur hexafluoride through the MARK XI UBA with the MARK VI mouthpiece unit.

11. Exercising at a work load of 1000 Kg-M/Min., breathing 30% oxygen - balance nitrogen through the MARK XI UBA with the Kirby-Morgan component mouthpiece unit.

12. Exercising at a work load of 1000 Kg-M/Min., breathing 30% oxygen - 70% sulfur hexafluoride through the MARK XI UBA with the Kirby-Morgan component mouthpiece unit.

GENERAL PROCEDURES

Each subject was instructed not to take any drugs for 24 hours prior to each day of experimentation. Subjects reported to the laboratory on the morning of the experiment after having a light carbohydrate breakfast. After the precordial electrodes had been attached and the esophageal balloon positioned, the subject rested quietly on the bicycle for 15 minutes.

Physiologic and equipment measurements (where appropriate) were then obtained for each inspired gas - activity level. All resting and exercise states were of 15 - 25 minutes duration. In the first part of each condition, the subject was allowed to reach a steady-state status. The physiologic and equipment measurements presented in this report are those measurements obtained during the final 5 - 10 minute steady-state status.

Resting state measurements for the different breathing gas - equipment conditions were always obtained prior to any of the exercise states. After all resting state measurements had been completed, the exercise state measurements were obtained. The sequence in which each breathing system was evaluated with a given gas, was varied from subject to subject. Moreover, the sequence of exercise conditions was varied for each subject, so that in one situation the subject would perform the heavy work first, and another time the light work load would be performed initially. Each exercise state was followed by a rest period of 20 - 30 minutes. During the lunch break, the subject was given a light carbohydrate lunch. At all times, the subjects were allowed water or non-caffeine containing soft drinks ad libium.

CALCULATIONS

A. Physiological Parameters

The measurements of ventilatory volume and of the composition of mixed expired gas obtained during each activity level-inspired gas condition were used to calculate the subject's oxygen consumption and carbon dioxide production. Oxygen consumption was calculated by using the formula (47):

$$\dot{V}_{O_2} = \left[F_{i_{O_2}} \times \frac{F_{e_{inert}}}{F_{i_{inert}}} - F_{e_{O_2}} \right] \times \left[\dot{V}_e \ \text{STPD} \right]$$

For the low resistance phase, carbon dioxide production was determined by the formula (47):

$$\dot{V}_{CO_2} = F_{e_{CO_2}} \times \dot{V}_e \ \text{STPD}$$

Because small amounts (0.1 - 0.2%) of carbon dioxide were often present in the inhaled gas when the MARK VIII and MARK XI were studied, carbon dioxide production was calculated by the formula (47):

$$\dot{V}_{CO_2} = \left[F_{e_{CO_2}} - \frac{F_{i_{inert}}}{F_{e_{inert}}} \times F_{i_{CO_2}} \right] \times \left[\dot{V}_e \ \text{STPD} \right]$$

The fractional concentration of inert gas (i. e., nitrogen or sulfur hexafluoride) in the inspired breathing mixture was calculated by subtracting the fractional concentration of oxygen (and CO_2 in the equipment studies) from unity. The fractional concentration of inert gas in the expired gas was determined by subtracting both the fractional concentrations of oxygen and of carbon dioxide from 1.0.

In order to determine alveolar ventilation, an assumption was first made of the magnitude of the subject's respiratory dead space (5). The formula $\dot{V}_A = \dot{V}_e - \dot{V}_D$ was then used to calculate alveolar ventilation.

Alveolar carbon dioxide tension was thus indirectly determined by using the formula (47):

$$P_{A_{CO_2}} = \frac{\dot{V}_{CO_2}}{\dot{V}_A} \times (P_B - 47)$$

Direct calculation of alveolar carbon dioxide tension was performed by taking the fractional concentration of alveolar carbon dioxide measured as previously described and multiplying by $(P_B - 47)$.

Pressure-Volume loops were constructed from the esophageal-mouthpiece pressure and volume tracings of at least three breaths for each activity level-gas mixture - breathing equipment condition. The calculated average tidal volume for that condition determined the volume of the breaths that were used. Exophageal-mouthpiece pressure tracings were free of any artifacts due to swallowing, coughing, etc.

For each 2 mm of volume change on the oscillograph paper, the corresponding esophageal-mouthpiece differential pressure was determined and recorded. The actual volume of which this 2 mm change in volume was equivalent was calculated from the volume calibration. The pressures for the same volumes for all the breaths were averaged and these averages used to construct the P-V loops (48). The elastic, flow resistive, negative and total work per breath was determined by measurement of the appropriate areas of the P-V loop with a planimeter.

A four-way analysis of variance (ANOVA) was performed to ascertain whether the activity level, the breathing mixture, the breathing system or an interaction of these factors had produced statistically significant ($P < 0.05$) changes. The values obtained for intrinsic mechanical work of breathing were plotted against ventilation and a best fit curve drawn by eye. A polynomial regression analysis was performed on this mechanical work of breathing data but was not available in time for inclusion in this report.

B. Equipment Parameters

The external respiratory work (W) required to breath against the resistance imposed by underwater breathing apparatus and its constituent components can be determined by the integration of gas volume and pressure. This integration is formulized as follows:

$$W = \int P dV$$

Cooper (18) stated that volume changes during resistive breathing were similar to a sine wave and the derivative of volume was best measured by using the formulas of a sine wave. Contrary to what Cooper found with his subjects, in our study the pattern of breathing of subjects' respiring through UBAs was not always sinusoidal. For this reason Silverman's method of measuring external respiratory work (57) was employed. Accordingly, mean differential pressure and flow rates were calculated in the following manner:

I. TOTAL EXTERNAL RESPIRATORY WCRK

1. Low Resistance Systems

The work that the subject did while breathing against the low resistance system was measured as the sum of external work done during exhalation and inhalation. The mean mouthpiece to ambient differential pressure and volume changes for each of the respiratory phases were measured and used in the calculation of work. The sum of work done in both phases was multiplied by the respiratory frequency (f) to give the total rate of work. The following expression was used:

$$\text{Work Rate } (\dot{w}) = \text{Mean differential pressure } (\bar{P}d) \times \text{volume } (V) \times \text{respiratory frequency } (f)$$

2. High Resistance Systems

The subjects breathing through the semi-closed circuit underwater breathing apparatus in this study were positive pressure breathing. One result was that the subjects had to actively work during expiration to oppose the pressure within the apparatus. During inhalation the subject may or may not be required to expend energy against the equipment. According to current references (12, 19) a mouthpiece pressure below the ambient pressure during inspiration is indicative of work being done by the subject; moreover, a mouthpiece pressure greater than the ambient pressure indicated no work being done by the subject. In the light of these interpretations, it was taken that during the period in which the mouthpiece pressure was below ambient pressure, the subject was doing work on the apparatus, and the mean pressure (mean negative differential pressure) during this same period was the force accounting for the corresponding flow rate. The following descriptive formulae were used:

Exhalation work rate ($\dot{W}_e$) = Mean differential pressure x flow rate

Inhalation work rate ($\dot{W}_i$) = Mean negative differential x flow rate

Total work rate = $\dot{W}_i + \dot{W}_e$

II. COMPONENT WORK

a) Mouthpiece

The work done against the mouthpiece was determined in two parts; the work done against the expiratory check valve and its connectors and tubing, and the work done against the inspiratory check valve and its connecting tubing. Each mouthpiece to bag differential pressure was correlated with flow. The following formulae were employed:

$\dot{W}_e$ = Mean mouthpiece to exhalation bag differential pressure x flow rate

$\dot{W}_i$ = Mean mouthpiece to inhalation bag differential pressure x flow rate

b) Pop-off Valve

The work done against the pop-off valve is dependent upon the pressure setting of the valve and the flow resistance imposed by the orifices of the valve. Immediately before each condition the pop-off valve was set against the injection rate so that the valve relieved at +5 - +6 cm H_2O (static setting). However, during the tests it was observed that the valve would open and close at a pressure (dynamic setting) something less than the static setting (usually 1-2 cm H_2O). The mean differential pressure accounting for gas flow through the valve was assumed to equal the mean pressure during the period in which the valve was open. Mean flow rate through the valve was calculated to equal the gas injection rate into the system less the oxygen consumption. The following formulae were used:

Mean flow rate through valve ($\dot{V}_{po_v}$) = injection rate - $\dot{V}_{O_2}$

Work Rate = $\dot{V}_{po_v}$ x mean differential pressure

c) Cannister

The force required for flow through the carbon dioxide absorbent cannister was measured as the mean differential pressure from the inlet side of the cannister to the outlet side. The flow rate through the cannister ($\dot{V}_c$) was measured as the ventilatory volume ($\dot{V}_e$) less the volume of gas exhausted through the pop-off valve (which was determined in the preceding section). Work done against the cannister was calculated using the following formula:

$$\text{Work Rate} = \dot{V}_c \times \bar{P}_d$$

d) Wasted Work

An attempt was made to correlate the external respiratory work done on the various components of the UBA with the total external respiratory work expended by the subject using this apparatus. It was assumed that the discrepancy between the measured total external respiratory work and the sum of the work done against individual components of the UBA (cannister work, pop-off valve work, mouthpiece work) resulted from work lost to the system -- in other words, wasted work. Wasted work was calculated by means of the formula:

$$\text{Wasted Work Rate} = \text{Total external respiratory work rate} - \text{Component work rate}$$

RESULTS

SUBJECTIVE EFFECTS AND GENERAL OBSERVATIONS

Inhalation of 70% sulfur hexafluoride - 30% oxygen produced narcosis. Some subjects were markedly affected; others minimally so. The subjects reported mild paresthesias, usually described as tingling and numbness of the hands and feet and occasionally around the lips. Other symptoms reported were lightheadedness, a sensation of being drunk, nausea, sleepiness, and feelings of euphoria or paranoia. Auditory effects usually an accentuation of low tones was also experienced.

Subjectively, the level of narcosis was increased when the subjects rested with their eyes closed. Under these conditions a subject would occasionally fall asleep. During the exercise states, the subjects reported that the level of narcosis induced by SF_6-O_2 inhalation was less intense. During subsequent exposures to sulfur hexafluoride narcosis, the subjects reported fewer subjective effects and a lesser degree of intoxication.

From the standpoint of breathing resistance, the subjects were unanimous in their selection of the low resistance system as the most comfortable to work with. The MARK XI UBA with the Kirby-Morgan component mouthpiece assembly was considered difficult to breath at the heavy work level. The MARK VIII and MARK XI with the MARK VI mouthpiece unit were especially disliked and drew severe complaints at the high work level. All the subjects stated that the Mark XI had more expiratory resistance than the Mark VIII, and that the Mark XI pop-off valve seemed more difficult to relieve.

Breathing SF_6-O_2 through the Mark VIII and Mark XI with the Mark VI mouthpiece unit was very difficult. All the subjects were visibly laboring at the completion of 15 minutes of heavy work breathing SF_6-O_2 through this equipment. One subject, R. V., was unable to complete more than 12 minutes of work in this situation because of exhaustion. Subject W. L. had no difficulty completing 15 minutes of heavy exercise breathing sulfur hexafluoride through the UBA's. However, after breathing SF_6-O_2 through the Mark VIII he complained of a headache (his $P_{A_{CO_2}}$ during this condition was 65 mm Hg.).

The three subjects who participated in the evaluation of the Mark XI as well as that of the Mark VIII appeared to be laboring less and had fewer complaints about breathing resistance in the later experiments than in the earlier studies.

While the subject W. L. was exercising at the heavy work load breathing SF_6-O_2 through the Mark XI with the Kirby-Morgan mouthpiece assembly, the gas injection rate into the UBA fell from 14.8 L/min to 9.2 L/min. This resulted in an inhalation bag oxygen percentage of 17.2% instead of the desired 30%. W. L.'s respiratory minute volume, alveolar carbon dioxide tension and other physiological parameters for this condition should be evaluated with this inspired oxygen percentage in mind.

PHYSIOLOGICAL PARAMETERS

Each of the parameters which were studied in this experiment will be analyzed from the standpoint of the effects of the inspired gas, the effects of the breathing system and the effects of the activity level. The results for individual subjects are presented in Tables 1A - 6.

Oxygen Consumption, Carbon Dioxide Production and Respiratory Exchange: Tables 4 - 6.

As work load increased, there was a significant ($P < 0.01$) linear increase in the subject's utilization of oxygen (Figure 9). Oxygen consumption during rest and exercise was increased during sulfur hexafluoride inhalation through the low resistance system. When nitrogen-oxygen or sulfur hexafluoride-oxygen was breathed through the MARK VIII and MARK XI UBA, oxygen consumptions during heavy work were significantly ($P < 0.01$) lower than with the low resistance system. Moreover, there was a significant ($P < 0.01$) degree of interaction between the MARK VIII and the activity level in producing this decrease.

With exercise the carbon dioxide production rose disproportionately to the oxygen uptake, the mean respiratory exchange quotient approaching unity in the heavy work state (Figure 1(
Carbon dioxide production during sulfur hexafluoride inhalation with the low resistance system and with the underwater breathing

TABLE 4 Mean Values of Physiological Parameters Measured on Six Subjects during REST While Breathing N_2-O_2 and SF_6-O_2 Mixtures through Low Resistance Equipment, the MARK VIII and MARK XI UBA with the MARK VI Mouthpiece Unit and the Kirby-Morgan Component Mouthpiece Assembly.

* 3 Subjects

Inspired Gas	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2 *	SF_6-O_2 *	N_2-O_2 *	SF_6-O_2*
Equipment	Low Res	Low Res	MARK VIII	MARK VIII	MARK XI + MK VI M.P.	MARK XI + MK VI M.P.	MARK XI + K-M	MARK XI + K-M
$\dot{V}_e$ L/Min. BTPS	8.78	6.30	8.87	7.45	8.09	7.10	8.45	8.14
f Br/min.	12.2	11.8	9.7	9.0	10.5	10.5	9.9	12.4
V_t Liters BTPS	.800	.708	1.048	.971	1.267	.942	1.462	1.135
O_2 Consump. (L/min.) STPD	.302	.318	.258	.201	.275	.239	.276	.335
O_2 Production (L/Min.) STPD	.197	.159	.214	.163	.188	.168	.192	.201
R	.65	.50	.83	.81	.70	.71	.68	.60
Calculated $P_{A_{CO_2}}$ mm Hg	37.9	39.1	33.6	32.5	35.7	39.9	34.4	42.9
Measured $P_{A_{CO_2}}$ mm Hg	37.6	37.9	36.9	40.1	39.5	38.5	41.6	41.0
Pulse Rate (Beats/Min.)	65	65	68	64	72	73	74	71

TABLE 5 Mean Values of Physiological Parameters Measured on Six Subjects during MODERATE WORK While Breathing N_2-O_2 and SF_6-O_2 Mixtures through Low Resistance Equipment, the MARK VIII UBA and MARK XI UBA with the MARK VI Mouthpiece Unit and the Kirby-Morgan Component Mouthpiece Assembly.

* 3 Subjects

Inspired Gas	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2 *	SF_6-O_2 *	N_2-O_2 *	SF_6-O_2*
Equipment	Low Res	Low Res	MARK VIII	MARK VIII	MARK XI + MK VI M.P.	MARK XI + MK VI M.P.	MARK XI + K-M	MARK XI + K-M
$\dot{V}_e$ L/Min. BTPS	25.57	25.20	27.26	21.98	22.84	21.78	27.82	20.44
f Br/min.	21.3	19.4	17.2	15.0	15.0	15.5	18.1	16.1
V_t Liters BTPS	1.341	1.371	1.804	1.538	1.703	1.536	1.803	1.492
O_2 Consump. (L/min.) STPD	1.016	1.152	1.011	.988	.769	1.015	1.082	.998
O_2 Production (L/Min.) STPD	.812	.796	.926	.781	.773	.767	1.041	.801
R	.80	.69	.92	.82	1.01	.76	.98	.81
Calculated $P_{A_{CO_2}}$ mm Hg	39.6	38.8	39.5	42.5	39.9	41.7	44.7	47.9
Measured $P_{A_{CO_2}}$ mm Hg	40.4	40.2	43.2	45.9	46.8	43.8	46.8	46.0
Pulse Rate (Beats/Min.)	113	108	114	110	115	123	132	132

TABLE 6 Mean Values of Physiological Parameters Measured on Six Subjects during HEAVY WORK While Breathing N_2-O_2 and SF_6-O_2 Mixtures through Low Resistance Equipment, the MARK VIII UBA and MARK XI UBA with the MARK VI Mouthpiece Unit and the Kirby-Morgan Component Mouthp[illegible]e Assembly.

* 3 Subjects

Inspired Gas	N_2- O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2 *	SF_6-O_2 *	N_2-O_2 *	SF_6-O_2*
Equipment	Low Res	Low Res	MARK VIII	MARK VIII	MARK XI + MK VI M.P.	MARK XI + MK VI M.P.	MARK XI + K-M	MARK XI + K-M
$\dot{V}_e$ L/Min. BTPS	47.60	43.57	43.58	35.91	36.70	31.69	41.29	34.79
f Br/min.	26.4	23.4	21.2	20.5	20.5	18.0	22.0	19.2
V_t Liters BTPS	1.877	1.925	2.140	1.795	1.987	1.888	2.190	2.055
O_2 Consump. (L/min.) STPD	1.810	2.051	1.604	1.621	1.362	1.518	1.657	1.346
O_2 Production (L/Min.) STPD	1.586	1.579	1.620	1.406	1.364	1.333	1.638	1.368
R	.88	.77	1.01	.88	1.0	.88	1.01	1.02
Calculated $P_{A_{CO_2}}$ mm Hg	37.3	41.2	41.2	45.9	43.3	48.2	45.7	44.1
Measured $P_{A_{CO_2}}$ mm Hg	37.8	41.9	43.6	48.6	46.9	48.7	50.7	47.8
Pulse Rate (Beats/Min.)	154	148	161	155	156	158	162	166

apparatus was significantly ($P < 0.05$) lower than when nitrogen-oxygen was breathed.

Pulse Rate:

Tables 4 - 6

Exercise breathing nitrogen-oxygen through the low resistance system significantly ($P < 0.01$) increased heart rate (Figure 11). This increase tended to be linear. Sulfur hexafluoride inhalation did not significantly affect heart rate. During both rest and exercise, heart rate was higher when the subject was using the MARK VIII and MARK XI than when he was breathing through the low resistance system. Those increases caused by using the MARK XI were statistically significant ($P < 0.05$).

Pulmonary Ventilation and Alveolar Gases:

Tables 4 - 6

One of the most striking findings of this study was the wide variability in the ventilatory response to exercise. Subject W. L. respired about 30 L/min while breathing sulfur hexafluoride through the low resistance system and working at the heavy work load. Under the same conditions, subject R. L. breathed 68 L/min.

Exercise while breathing 30% oxygen - balance nitrogen through the low resistance system increased respiratory minute volume from an average of 8.78 L/min at rest to 25.57 L/min during moderate work and to 47.6 L/min during heavy work (Figure 12). Inhalation of sulfur hexafluoride through the low resistance system significantly ($P < 0.05$) diminished respiratory minute volume at all activity levels. In the conditions where nitrogen-oxygen was breathed through the MARK VIII UBA, respiratory minute volume was slightly increased above the low resistance N_2-O_2 control values at rest and during moderate work, but during heavy work ventilation was decreased. The combination of SF_6-O_2 with the MARK VIII caused a profound hypoventilation during both moderate and heavy work.

Figure 13 compares the respiratory minute volume of subjects breathing through the MARK VIII with the RMV of subjects breathing through the MARK XI with the MARK VI mouthpiece unit. During nitrogen-oxygen breathing, the MARK XI with the MARK VI mouthpiece caused a greater degree of hypoventilation than did the MARK VIII. The respiratory minute volumes of subjects breathing sulfur hexafluoride through the MARK VIII and the MARK XI with the MARK VI mouthpiece were essentially the same.

Figure 14 shows the respiratory minute volume of subjects breathing through the MARK VIII and the MARK XI with the Kirby-Morgan mouthpiece unit. With both nitrogen-oxygen and sulfur hexafluoride mextures, there was essentially no difference in the respiratory minute volumes of the subjects breathing these gases through the MARK VIII or the Kirby-Morgan component mouthpiece assembly.

The magnitude of respiratory frequency varied considerably from one subject to the next. One subject's resting respiratory frequency ranged from 2.5 to 5.5 breaths/min. During exercise at the heavy work rate, it increased to 9.5 to 15 breaths/minute. Another subject's frequency of breathing was between 10 - 15 breaths/minute at rest, and 29 - 34 breaths/minute at heavy work. As respiratory impedance was increased though, all the subjects had progressively lower respiratory frequencies and generally larger tidal volumes.

Both the nature of the breathing medium and the nature of the breathing equipment affected the respiratory pattern. Respiratory frequency rose significantly ($P < 0.01$) with exercise (Figure 15). Inhalation of sulfur hexafluoride through the low resistance system decreased respiratory frequency both at rest and during exercise.

Breathing through the MARK VIII and MARK XI significantly ($P < 0.05$) lowered the frequency of breathing. The most marked falls in respiratory frequency occurred when sulfur hexafluroide was breathed through the UBA. In this condition there was a signficant ($P < 0.05$) degree of interaction between the work level and the gas and between the work level and UBA in causing this decrease.

Added resistance to breathing resulted in an increased time for inspiration and expiration (Figures 16-17). The increase was greatest for expiration, especially at rest and during moderate work. Inhalation of sulfur hexafluoride through the MARK VIII lengthened each phase of respiration by the greatest amount.

Like respiratory frequency, tidal volume (Figure 18) significantly ($P < 0.01$) increased with exercise. Inhalation of sulfur hexafluoride through the low resistance system caused a slight increase in tidal volume during exercise. The largest increases in tidal volume were found in the condition where the subjects were breathing nitrogen-oxygen through the MARK VIII and the MARK XI. When, however, sulfur hexafluoride was respired through these apparatus, both at rest and during exercise, tidal volume was diminished to a level below that of the N_2-O_2 situation with the equipment.

Measured alveolar carbon dioxide tension (Figure 19) rose slightly during moderate exercise while breathing N_2-O_2 through the low resistance system. During heavy work it returned to about resting levels. During inhalation of sulfur hexafluoride with this breathing system, the alveolar carbon dioxide tensions at rest and during moderate work were at the nitrogen-oxygen values. During heavy work, though, measured $P_{A_{CO_2}}$ rose to 41.9 mm Hg.

During inhalation of nitrogen-oxygen through the MARK VIII, alveolar carbon dioxide tension at rest was close to the control value. During moderate work $P_{A_{CO_2}}$ significantly ($P < 0.05$) rose to 43.2 mm Hg and during heavy work to 43.6 mm Hg. Performance of exercise and the use of the MARK VIII were found to significantly interact in producing these increases. Breathing dense gas through the MARK VIII produced a marked degree of carbon dioxide retention. Resting alveolar carbon dioxide tension was 40.1 mm Hg and with moderate work it rose to 45.7 mm Hg; during heavy work mean measured $P_{A_{CO_2}}$ was 48.6 mm Hg.

Inhalation of N_2-O_2 with the MARK XI with both the MARK VI mouthpiece and with the Kirby-Morgan component mouthpiece caused a greater amount of carbon dioxide retention than was present with the MARK VIII, (Figures 20-21). However, when the sulfur hexafluoride was breathed through the two MARK XI arrangements, the measured alveolar carbon dioxide tensions were no higher than for the MARK VIII.

The measured and calculated alveolar carbon dioxide tensions were quantitatively very close for a given activity level in the low resistance breathing system regardless of whether nitrogen-oxygen or sulfur hexafluoride - oxygen mixtures were breathed. However, when the subjects breathed through the MARK VIII and MARK XI, the calculated alveolar carbon dioxide tensions were consistently lower than the measured values.

TOTAL INTRINSIC RESPIRATORY WORK

Figures 22 through 25 illustrate the intrinsic respiratory work required to breath nitrogen-oxygen through the low resistance system and through the underwater breathing apparatus. Figures 26 through 29 depict the intrinsic respiratory work of subjects breathing SF_6-O_2 through these systems. Exercise caused a significant ($P < 0.01$) increase in the intrinsic respiratory work for all experimental situations.

The work of breathing nitrogen-oxygen was least with the low resistance breathing system. Breathing nitrogen-oxygen through the UBAs increased intrinsic respiratory work. The least increase in intrinsic work of breathing occurred using the MARK XI with the MARK VI mouthpiece unit; the largest increase was present breathing with the MARK VIII. The intrinsic work of breathing N_2-O_2 through the MARK XI with the Kirby-Morgan component mouthpiece assembly was less than that required for the MARK VIII but more than that required for the MARK XI - MARK VI mouthpiece combination. Up to respiratory minute volumes of 40 L/min, the difference in total intrinsic work of breathing with the low resistance system and with the UBAs was within 2 Kg-M/min. Above 40 L/min, the intrinsic work of breathing through the MARK VIII increased at a greater rate than that of the other breathing systems. The intrinsic work of breathing through the MARK XI

UBA mouthpiece combinations increased linearly as ventilation increased.

When sulfur hexafluoride was inhaled through a given breathing system, intrinsic respiratory work was greater than for the comparable nitrogen-oxygen condition. During SF_6-O_2 breathing intrinsic respiratory work was least using the low resistance breathing system. At low respiratory minute volumes breathing through the MARK XI with the Kirby-Morgan component mouthpiece required the greatest amount of intrinsic respiratory work. The MARK XI with the MARK VI mouthpiece required slightly less, and the MARK VIII the least. However, at ventilations above 32 L/min, the intrinsic work of breathing with the MARK VIII was greater than for the MARK XI combinations.

Elastic Work:

Figures 30 and 31 illustrate the changes in the elastic component of intrinsic respiratory work of subjects breathing nitrogen-oxygen and sulfur hexafluoride-oxygen mixtures through the low resistance system and with the UBAs. In all the experimental conditions exercise (which increased respiratory minute volume) caused a significant ($P < 0.01$) increase in the elastic component of work of breathing. When sulfur hexafluoride-oxygen was respired through the MARK VIII UBA, these factors significantly ($P < 0.05$) interacted to further increase elastic work of breathing. The elastic component of work of breathing was least increased during use of the low resistance system. The elastic work of breathing nitrogen-oxygen through the UBAs was quantitatively similar for all ventilations. When SF_6-O_2 was respired through the low resistance system, elastic work of breathing was slightly greater than for N_2-O_2 breathing with this system. Similarly, elastic work of breathing SF_6-O_2 through the UBAs was slightly greater than when N_2-O_2 was respired through these systems.

Flow Resistive Work:

The work required to overcome intrinsic respiratory flow resistance while breathing nitrogen-oxygen and sulfur hexafluoride-oxygen through the low and high impedance systems is shown in Figures 32 and 33. Flow resistive work was significantly ($P < 0.01$) increased by exercise (i. e. increased ventilation) with all breathing systems. When nitrogen-oxygen was breathed at low and moderate ventilations, there was little difference in flow resistive work between the low resistance system and the UBAs. At higher ventilations, flow resistive work was less with the MARK XI with the Kirby-Morgan component mouthpiece than with the low resistance system and other UBA conditions.

When sulfur hexafluoride-oxygen was breathed at low and moderate respiratory minute volumes, the flow resistive component of work of breathing was quantitatively very close to that for nitrogen-oxygen breathing. At high ventilations, the flow resistive component of work of breathing was appreciably increased by breathing dense gas. At high ventilations, flow resistive work was least when the subjects were respiring through the MARK XI UBA combinations, and greatest when they were breathing through the low resistance system.

Negative Work:

Figures 34 and 35 show the changes in negative respiratory work while breathing N_2-O_2 and SF_6-O_2 mixtures through the low impedance system and through the UBAs. When nitrogen-oxygen was breathed at low ventilations, negative work of breathing was essentially the same with all the breathing systems. Exercise (i.e. increasing RMV) significantly ($P < 0.01$) increased negative work, and at moderate and high ventilations, negative work was substantially different between the various breathing systems. The least expenditure of negative work was required with the low resistance system. The greatest expenditure of negative work occurred while breathing through the MARK VIII at high ventilations, and the negative work of breathing nitrogen-oxygen through the MARK XI UBA combinations fell between that required for the other systems.

At low ventilations breathing sulfur hexafluoride-oxygen, the expenditures of negative respiratory work with the low resistance system and with the UBAs were quantitatively similar. Negative work was greatest at moderate ventilations when the subjects were breathing with the MARK XI combinations. At high ventilations, breathing a dense gas significantly ($P < 0.05$) diminished negative work. At these ventilations using the MARK XI UBA, negative work decreased, whereas with the low resistance system and the MARK VIII it rose, but remained at levels well below those found for N_2-O_2 breathing.

TOTAL EXTRINSIC RESPIRATORY WORK

The total extrinsic respiratory work required to breath nitrogen-oxygen through the different breathing systems is illustrated in Figure 36. The greatest amount of external respiratory work was expended breathing with the MARK XI with the MARK VI mouthpiece, the next greatest with the MARK VIII and the least with the MARK XI with the Kirby-Morgan component mouthpiece. There was relatively little difference between the UBAs in the external respiratory work rate up to 35 L/min. At respiratory minute volumes above this level, there was an increasing disparity between the various UBA conditions.

The only difference between the MARK XI UBAs in this study was in the mouthpiece assemblies which were used. It was assumed that the difference in extrinsic respiratory work rate between the two MARK XI conditions was due to the MARK VI mouthpiece. Based on this assumption, the difference in extrinsic respiratory work with the MARK XI combinations was measured at different ventilations and this difference subtracted from the work-ventilation curve for the MARK VIII. The resultant values were plotted to construct a theoretical curve for a combination of the MARK VIII with the Kirby-Morgan component mouthpiece. This curve shows that extrinsic respiratory work rate would be less with this combination, than with the other UBA combinations which were studied.

Breathing sulfur hexafluoride-oxygen mixtures increased total external respiratory work rate in all conditions above that present for nitrogen-oxygen breathing (Figure 36). The curves for the different breathing systems showed the same relationship to each other with SF_6-O_2 breathing as was present with N_2-O_2. At ventilations above 30 L/min with SF_6-O_2, there was a greater difference between the extrinsic respiratory work rates for the MARK VIII and the MARK XI combinations than with N_2-O_2. Again, a theoretical curve for the MARK VIII with the Kirby-Morgan component mouthpiece was plotted. The result was similar to that found for nitrogen-oxygen mixtures.

The relationship between external respiratory work as a percentage of total (intrinsic plus extrinsic) respiratory work and between ventilation when respiring N_2-O_2 with the different breathing systems is shown in Figure 37. The percentage of total respiratory work attributable to extrinsic resistance remains stable for all conditions with the exception of the MARK XI with the MARK VI mouthpiece. With this apparatus, the extrinsic work percentage rose from 20% at a resting ventilation of 8 L/min to 50% at 49 L/min. This is about 20% greater than found with the MARK VIII or MARK XI with the Kirby-Morgan component mouthpiece. With SF_6-O_2 breathing, the percentage of total respiratory work due to extrinsic work, increased with all breathing systems, including the low resistance system. The greatest increase in extrinsic work percentage was again found with the MARK XI with the MARK VI mouthpiece (Figure 38).

The average levels of extrinsic respiratory work for the different experimental situations are summarized in Tables 7 and 8 along with the average levels for intrinsic and total respiratory work.

Work Against Mouthpiece Assemblies:

The rate at which work was done to compensate for the resistance of the MARK VI and the Kirby-Morgan component mouthpieces was plotted against the respiratory minute volume (Figure 39). When N_2-O_2 gas mixtures were respired, the impedance of both mouthpieces increased as the respiratory minute volume increased. The work done while breathing with

	$\dot{V}_E$ L/Min.	Intrinsic Work Kg-M/min.	% of Total	Extrinsic Work Kg-M/min.	% of Total	Total Work Kg-M/min.
Low Resistance	8.8	0.8	91.9	.068	7.1	0.87
	25.4	2.95	79.7	0.75	20.3	3.7
	46.7	11.15	75.8	3.56	24.2	14.7
MARK VIII	7.52	0.75	58.6	0.53	41.4	1.28
	24.2	3.45	58.4	2.46	41.6	5.91
	42.65	9.0	49.2	9.28	50.8	18.28
MARK XI $\bar{c}$ KIRBY-MORGAN	11.0	2.0	75.2	0.66	24.8	2.66
	21.8	3.95	69.0	1.77	31.0	5.72
	37.1	6.7	59.3	4.51	40.2	11.21
MARK XI $\bar{c}$ MARK VI M.P.	10	2.0	74.6	0.68	25.4	2.68
	20.2	4.2	63.4	2.42	36.6	6.62
	39.4	8.25	48.9	8.63	51.1	16.88

TABLE 7. INTRINSIC, EXTRINSIC AND TOTAL RESPIRATORY WORK DONE BREATHING SF_6-O_2.

	$\dot{V}_E$ L/Min.	Intrinsic Work Kg-M/min.	% of Total	Extrinsic Work Kg-M/min.	% of Total	Total Work Kg-M/min.
Low Resistance	13.6	1.4	86.6	0.217	13.4	1.617
	27.3	3.35	89.5	0.392	10.5	3.742
	53.1	9.5	86.3	1.515	13.7	11.01
MARK VIII	6.8	0.75	63.5	0.432	36	1.18
	30.3	4.95	69.0	2.219	31	7.17
	50.0	11.8	66.8	5.85	33.2	17.65
MARK XI $\bar{c}$ KIRBY-MORGAN	7.4	1.15	76.8	0.347	23.2	1.497
	19.5	3.25	72.1	1.263	27.9	4.51
	46	7.7	68.4	3.55	31.6	11.25
MARK XI $\bar{c}$ MARK VI M.P.	8.3	1.3	80	0.325	20	1.625
	36.1	4.9	56.4	3.78	43.6	8.68
	49.0	6.2	49.8	6.24	50.2	12.44

TABLE 8. INTRINSIC, EXTRINSIC, AND TOTAL RESPIRATORY WORK DONE BREATHING N_2-O_2.

the MARK VI mouthpiece was approximately twice that required to breath with the Kirby-Morgan component mouthpiece. As respiratory minute volume increased, overcoming mouthpiece resistance required a greater fraction of the total extrinsic respiratory work load. When the work against the mouthpieces is expressed as percent of the total extrinsic respiratory work, the MARK VI mouthpiece accounted for 20-90% of the total extrinsic work, while the Kirby-Morgan mouthpiece accounted for 16 - 50% of the total extrinsic work (Table 9).

When SF_6-O_2 gas mixtures were breathed, there was a much greater increase in impedance with increasing minute volumes than with the N_2-O_2 gas mixtures. The MARK VI mouthpiece contributed greater resistance than did the Kirby-Morgan. The fraction of the total extrinsic work was 30 - 80% for the MARK VI and 30 - 60% for the Kirby-Morgan (Table 9).

Work Against Carbon Dioxide Absorbent Cannisters:

The resistance imposed by the carbon dioxide absorbent cannister was of small consequence when compared to the resistance imposed by the other components. The flat-can type cannister used in the MARK VIII assembly accounted for 3 - 6% of the total extrinsic respiratory work with N_2-O_2 gas mixtures; the cylindrical cannister of the MARK XI assembly accounted for 2 - 4% of the total work. With SF_6-O_2 gas mixtures, the work done on the carbon dioxide absorbent cannister of the MARK VIII increased to account for 3 - 8% of the total work load. The MARK XI cannister accounted for

Equipment	Gas Mixture	RMV (L/Min)	Mouth-piece	Component Work Rate (Kg-M/min.)			
				Pop-off Valve	Cannis-ter	Wasted	Total
MARK VIII	N_2-O_2	6.8	0.090	0.082	0.027	0.232	0.432
	N_2-O_2	30.3	1.581	0.352	0.117	0.168	2.219
	N_2-O_2	64.8	8.431	0.589	0.276	0.255	9.550
	SF_6-O_2	7.5	0.167	0.119	0.042	0.202	0.529
	SF_6-O_2	24.2	1.934	0.442	0.037	0.050	2.463
	SF_6-O_2	42.7	7.594	1.073	0.262	0.349	9.277
MARK XI & KIRBY-MORGAN COMPONENT MOUTH-PIECE ASSEMBLY	N_2-O_2	7.4	0.056	0.000	0.012	0.279	0.347
	N_2-O_2	19.5	0.395	0.524	0.010	0.334	1.263
	N_2-O_2	54.2	2.122	0.924	0.093	1.351	4.490
	SF_6-O_2	11.0	0.209	0.098	0.059	0.298	0.663
	SF_6-O_2	21.8	0.859	0.729	0.041	0.140	1.768
	SF_6-O_2	37.1	2.558	1.243	0.137	0.570	4.508

TABLE 9. COMPONENT WORK RATES FOR THE MARK VIII and MARK XI UBA WITH N_2-O_2 and SF_6-O_2.

3 - 9% of the total work. In comparison with one another, the MARK VIII cannister imposed a slightly greater resistance than did the MARK XI cannister (Table 9).

Work Against Pop-off Valves:

The work flow characteristics of the MARK VIII and MARK XI pop-off valves are presented in Figure 40. In tests using N_2-O_2, the pop-off valve of the MARK XI accounted for greater work rates than did the pop-off valve of the MARK VIII. A similar relationship existed between the two pop-off valves while using SF_6-O_2 gas mixtures, but work rates were larger.

Wasted Work:

Wasted work (or negative work) was greater with the MARK VIII UBA. The amount of wasted work ranged from 30 - 50% of the total extrinsic respiratory work expended with the MARK VIII and 30 - 80% of the total work with the MARK XI combinations when N_2-O_2 was respired. With SF_6-O_2 mixtures, the MARK VIII wasted work ranged from 4 - 40% and the MARK XI 13 - 45%. The greatest quantity of work was lost at low flow rates in both UBAs (Table 9).

Work Against All Components Except Mouthpiece:

The sum of the work loads imposed by the various components (excluding mouthpieces) of each apparatus is compared to one another in Figure 41. The sum of the component work rates of the MARK XI was greater than that of the MARK VIII with N_2-O_2 or SF_6-O_2 gas mixtures.

TOTAL RESPIRATORY WORK

The total (intrinsic plus extrinsic) respiratory work expended breathing nitrogen-oxygen with the different breathing systems is plotted in Figure 42 against ventilation. Up to ventilations of 32 L/min, the total work required for the different UBAs was for practical purposes, equal and showed a linear increase. At higher ventilations, the work levels for both MARK XI combinations continued to be equal but the total work with the MARK VIII increased more rapidly.

At all ventilations the total respiratory work when SF_6-O_2 was breathed was greatest with the MARK XI UBA with the MARK VI mouthpiece (Figure 43). At resting and moderate respiratory minute volumes, the expenditure of respiratory work was least with the MARK VIII. At ventilations over 28 L/min, the MARK XI with the Kirby-Morgan component mouthpiece required the least intrinsic and extrinsic work. A theoretical curve for the total respiratory work of the combination of the MARK VIII with the Kirby-Morgan component mouthpiece is plotted against ventilation in Figure 43. The plot shows that total respiratory work breathing sulfur hexafluoride-oxygen through this UBA combination is only slightly greater than that of the low resistance system.

DISCUSSION

SUBJECTIVE EFFECTS:

The subjective effects induced by breathing 70% sulfur hexafluoride closely mimic the introspective responses which occur while breathing 30% nitrous oxide and while breathing air at pressures of 8-10 atmospheres.

The marked variation in the sensitivity of different subjects to sulfur hexafluoride narcosis was impressive. Such variation has been previously reported with nitrous oxide narcosis (24). Wide variation in the susceptibility to nitrogen narcosis has often been noted (8). Sensations of drunkenness, euphoria, lightheadedness, and paresthesias of the extremities have repeatedly been reported in subjects narcotized with N_2O (9) and in divers who are narcotized while breathing compressed air at high pressures.

Case and Haldane (15) reported development of some degree of tolerance to the effects of nitrogen narcosis. Bradley (9) found that tolerance developed to the effects of nitrous oxide narcosis. The mechanism by which this tolerance to narcosis is attained has yet to be determined.

The subjective evaluations of the MARK VIII and the MARK XI combinations were that the breathing resistance with dense gas was too severe during heavy work. One subject succinctly stated: "No one would or could work that hard in the water with any of this gear." The MARK XI with the Kirby-Morgan was adjudged the best of the three UBAs, but this evaluation is not particularly confirmed by objective measurements.

This study once again points out the limitation of subjective evaluation of the breathing resistance in underwater breathing equipment. The subjects who participated in the complete series of studies had progressively fewer complaints about breathing resistance with each succeeding experiment. It appears that a training factor to resistive breathing was present and this diminishes the reliability of subjective evaluation. This phenomenon has previously been reported by Silverman (57). It is especially noteworthy in our study because two of the three subjects were experienced divers and presumably accustomed to breathing with high resistance diving equipment.

PULSE RATE:

The cardiac rates of our subjects were increased when they breathed with the underwater breathing apparatus. This agrees with previous findings for resistive (11, 58) and positive pressure (21) breathing.

Cardiac output is reduced by resistive (13) and positive pressure (21) breathing. This reduction in cardiac output is an effect of the increased intrathoracic pressure and decreased venous return to the right atrium. The tachycardia that occurs probably results from the reduction in effective filling pressure of the right side of the heart and from activation of carotid baroreceptors.

OXYGEN CONSUMPTION, CARBON DIOXIDE PRODUCTION AND RESPIRATORY EXCHANGE QUOTIENT:

The data obtained during exercise breathing nitrogen-oxygen through the low resistance system demonstrates the familiar thermodynamic relationship of whole body oxygen consumption to work load. The similar concurrent changes in carbon dioxide production and respiratory exchange quotient are well described (4) and warrant no comment.

Breathing sulfur hexafluoride-oxygen through the low resistance system, the subjects consumed significantly larger amounts of oxygen than when breathing nitrogen-oxygen. Moreover, when SF_6-O_2 was respired through both the low resistance system and through the UBAs, carbon dioxide production was significantly decreased.

The increase in oxygen consumption may be due to the greater cost of breathing a dense gas. Glauser, et. al. (25) found that the oxygen cost of breathing 36 L/min of a SF_6 mixture, 4.1 times as dense as air at sea level, was increased 5 cc/L/min. In our study the oxygen cost of breathing 25 L/min of a sulfur hexafluoride-oxygen mixture, 3.9 times as dense as sea level air, was increased 5.4 cc/L/min. At a ventilation of 43 L/min, oxygen consumption was increased 5.6 cc/L/min.

In studies conducted at high pressures of helium-oxygen, the oxygen consumption of resting and exercising subjects has been found to be increased (10, 28, 55). This increase in oxygen utilization has been attributed to the increased work of breathing a dense breathing mixture and to changes in thermal balance. Bradley, et. al (10) studied the oxygen uptake of subjects who were respiring 57 L/min of a $He-O_2$ mixture which was 3.7 times the density of sea level air. The oxygen cost of breathing of these subjects was increased 4.9 cc/L/min. Subjects breathing 30 L/min of helium-oxygen at 1000 feet of sea water (a density increase of 4.8 times that of air at sea level) had increases in the oxygen cost of respiration of 4.7 cc/L/min (55). The increases in oxygen consumption of our subjects breathing 70% SF_6 through a low resistance system are quantitatively in agreement with the findings of Glauser (25) for SF_6, and with the results of others (10, 55) for helium-oxygen mixtures of equivalent density.

Metabolic derangements induced by breathing SF_6 could account for the increased oxygen uptake and concurrent diminished carbon dioxide output. The narcosis induced by sulfur hexafluoride-oxygen inhalation suggests that SF_6 may possess properties similar to those of other inert gases with narcotic properties. An extensive review of the physiochemical and pharmacologic properties of the noble gases was made by Featherstone and Muehlenbacher (22). In some studies which they cited, noble gases such as xenon did not affect cellular respiration and oxidative phosphorylation. In other studies they state that cellular oxygen consumption was increased and anaerobic glycolysis decreased in the presence of these gases. This latter study suggests that the inert gas acted as an uncoupler of oxidative phosphorylation. This process characteristically increases cellular oxygen uptake and decreases the usage of terminal phosphate acceptors (glucose plus hexokinase). With a decrease in anaerobic input into the Krebs-Cycle, the cellular respiratory chain would have to depend on other substrates, and there would possibly be a decrease in carbon dioxide production.

The most plausible explanation for the increase in oxygen uptake of subjects breathing SF_6 is simply that work of breathing is greater. However, in light of the diminished carbon dioxide production of subjects breathing SF_6, an effect by sulfur hexafluoride upon oxidative metabolism cannot be ruled out, and further study will be required.

The oxygen consumption of our subjects breathing with the UBAs was consistently decreased during heavy work. Decreases in the oxygen consumption of subjects who are breathing against added resistance during heavy work have been previously reported (20, 57, 58, 59).

That oxygen consumption can be decreased by breathing against externally imposed resistance and increased by breathing a dense gas poses an apparant paradox. In both situations, it appears that the only factor involved is one of greater work of breathing. However, there seem to be two factors which determine whether oxygen consumption is reduced or elevated in resistive breathing. The first determinant is work level; the second is the arrangement and amount of added resistance against which the subject is breathing.

Subjects appear to increase their oxygen uptake to compensate for the increased metabolic work of breathing against high resistance at rest (13), against moderate resistance during moderate work (57), and against low resistance during heavy work. If inspiratory resistance is appreciably greater than expiratory, but the combined resistance not too great, this phenomenon is particularly apparent (57).

Table 10 shows the flow resistance to inspiration and to expiration with the different gases and breathing systems employed in the present study. These resistances were obtained at flow rates of 85 L/min according to the method of Silverman (57). It is obvious that when sulfur hexafluoride was respired through the low resistance system, inspiratory and expiratory resistances were about equal and the combined degree of extrinsic resistance was relatively low. In this condition the subjects increased their oxygen uptake above the control values.

GAS	SYSTEM	INSPIRATION mm H_2O	EXPIRATION mm H_2O
N_2-O_2	LR	4	2
SF_6-O_2	LR	20	17
N_2-O_2	MARK VIII	45	65
SF_6-O_2	MARK VIII	72	100
N_2-O_2	MARK XI-MK VI	34	100
SF_6-O_2	MARK XI-MK VI	63	120
N_2-O_2	MARK XI-KM	15	90
SF_6-O_2	MARK XI-KM	35	105

TABLE 10. Resistance to Inspiration and to Expiration of N_2-O_2 and SF_6-O_2 at a Flow Rate of 85 L/min, through the low resistance system, through the MARK VIII and through the MARK XI with the MARK VI mouthpiece and with the Kirby-Morgan component mouthpiece.

There is a marked increase in breathing system resistance between the low resistance/SF_6 condition and the UBA/N_2-O_2 condition. Most of the increase is on the expiratory side. When expiratory resistance is considerably greater than inspiratory, and when there is a considerable amount of resistance to both inspiration and expiration, oxygen uptake during heavy work is lower than control values (58). Thus the results of our study are in agreement with Silverman (58) and others (11, 59).

Most investigators have considered that this reduction in oxygen utilization represents the contracture of an oxygen debt (18, 20, 57). Tabakin (59) hypothesized that the reduction in oxygen uptake during resistance breathing results from an acute reduction in pulmonary blood flow. This reduction in pulmonary blood flow would be a result of the increased intrathoracic pressure which was impairing pulmonary capillary blood flow and impairing oxygen transfer.

That our findings of reduced oxygen uptake during heavy work breathing through the UBAs results from spurious data cannot altogether be discounted. The small size of the sample group could be responsible. The possibility of a systematic error in the design or conduct of the experiment also cannot be completely ruled out. Failure to accurately reset the bicycle ergometer at the same work level could occur, but it is improbable that an error of this sort would be systematic.

Failure to obtain representative samples of inspired and/or mixed expired gas could result in erroneously low values for oxygen consumption. A potential source of error in this study was the gas collection technique which was employed with the UBAs. Of necessity the breathing bags of the underwater breathing apparatus were used as mixing chambers. The volume of each bag was about 4 liters; most mixing chambers have volumes of 8 - 10 liters. Thus, there may not have been adequate hemogenization of the expired dead space gas with alveolar gas in the exhalation bag, and of the injected gas with the CO_2 scrubbed gas in the inhalation bag. We utilized the greater than ambient intra-bag pressure to drive the gas sample from the breathing bag into the sample bags. Gas flow into the sample bag was continuous, monitored by flow-meters and regulated by valves. Flow into both sample bags was appreciably greater when the subject exhaled, increasing the pressure within the underwater breathing apparatus. The cyclic nature of this sampling method together with incomplete mixing of inspired or expired gas could, therefore, provide unrepresentative gas samples.

That the gas collection method used with the UBA's was inadequate is considered unlikely. In preliminary studies, the oxygen and carbon dioxide content of both breathing bags was continuously monitored with fast-response paramagnetic oxygen and infra-red CO_2 analyzers. Once a steady-state had been achieved, there was minimal moment-to-moment fluctuation in readings. Moreover, it is difficult to explain why the UBA gas collection method should be inadequate during heavy work, and yet apparently adequate during rest and moderate work where no consistent changes in oxygen consumption were observed.

Therefore, it would seem that there is a level of added resistance, particularly if imposed on expiration which during heavy work causes oxygen uptake to be less than normal. Because of this situation, assessment of the respiratory system by measurement of the change in oxygen consumption is not valid. This reduced oxygen consumption probably indicates that an oxygen debt is being contracted. Subjects who use the MARK VIII and the MARK XI combinations during heavy work have marked reductions in oxygen uptake and presumably incur large oxygen debts. Measurements of lactic and pyruvic acid and of recovery oxygen consumptions of subjects using underwater breathing apparatus during hard work will be required to delineate the nature and extent of this oxygen deficit.

PULMONARY VENTILATION AND ALVEOLAR GASES

It is well recognized that within the diver population there exists wide variation in the ventilatory response to exercise. That some divers hypoventilate and retain carbon dioxide during exertion has been reported by Lanphier (39) and other investigators (26). Why these divers' ventilatory response to exertion is inadequate, whereas others' is normal is simply not clear at this time.

Many divers have been shown to be markedly insensitive to hypercapnia and acid products of metabolism as stimuli to respiration (38, 54). Some investigators have considered this phenomenon to represent an adaptive response to the conditions of diving and to be responsible for the hypoventilation and carbon dioxide retention of divers during exercise (54). An imperfect correlation has been made between length of diving experience and carbon dioxide retention during work (38). The imperfectness of this correlation is demonstrated in our study. Subject W. L. with 13 years of diving experience, markedly hypoventilated during exercise. R. L. with no diving experience tended to retain carbon dioxide during exertion. R. V., with 10 years of diving experience, often hyperventilated.

In divers whose ventilatory response to exercise is inadequate, breathing dense gas such as air at increasing depths markedly worsens the degree of hypoventilation and carbon dioxide retention (39). In other more normal subjects, breathing air (35) and helium-oxygen mixtures (28) at depth have been reported to produce lesser degrees of hypoventilation and CO_2 retention. Inspired oxygen tension, narcotic depression of respiratory centers and increased work of breathing are factors that have been implicated to account for this phenomenon (35, 39).

Elevations in inspired oxygen tension have been shown to increase alveolar ventilation at rest (30), but to cause hypoventilation during exercise (36, 53). In our study where inspired oxygen tension was kept constant the changes in ventilation which we observed cannot be explained on this basis.

Hypoventilation and carbon dioxide retention occurred when sulfur hexafluoride-oxygen was breathed through the low resistance system during heavy work. Both at rest and during exercise, there were marked reductions in ventilation and rises in alveolar carbon dioxide tension when SF_6 was respired through the UBA's. Sulfur hexafluoride possesses narcotic properties and depression of respiratory centers which would account for this hypoventilation. However, Glauser (25) has shown that the minute volume of subjects breathing 7% carbon dioxide in a 73% sulfur hexafluoride - 20% oxygen mixture was the same as when they breathed 7% CO_2 in air. This implies that sulfur hexafluoride does not depress respiratory centers through any narcotic action.

Numerous studies have shown that increased work of breathing causes hypoventilation and carbon dioxide retention (13, 20, 57, 58, 59). In our study, work of breathing was increased by respiring dense gas and by breathing against imposed external resistance. Each of these factors by itself caused hypoventilation and carbon dioxide retention during exercise. When these factors were combined and work of breathing was greatest, hypoventilation and carbon dioxide retention was most pronounced. Thus our subjects apparently chose to tolerate hypercapnia rather than expend the effort required to increase ventilation and maintain alveolar carbon dioxide tension at normal levels (13).

Indirect calculation of alveolar carbon dioxide tension has been shown to give more accurate values than those obtained by end-tidal sampling during exercise (4). In the present study, this situation is not valid. First of all, as was discussed in the Method and Materiels Section, we did not measure the actual end-tidal carbon dioxide tension. Secondly, in the conditions where our subjects were breathing with the underwater breathing apparatus, the magnitude of physiological dead space was probably larger than was assumed for purpose of the calculations. This underestimation of dead space is thought to account for the discrepancy between the direct measurements and the lower calculated values for $P_{A_{CO_2}}$. Increases in physiological dead space could be expected to result from positive pressure breathing (21), breathing dense gas (40) and breathing against externally imposed resistance.

As resistance to breathing was increased the hypoventilation and hypercapnia that occurred was accompanied by a progressive fall in respiratory frequency and generally an increase in tidal volume. A breathing pattern of lower respiratory frequency and larger tidal volumes occurs while breathing dense gas (9, 30, 35, 53) and while breathing against externally imposed resistance (13, 57). It is teleologically satisfying to think that the observed changes in respiratory pattern represent an adaptive mechanism to minimize work of breathing (48). It is difficult though to postulate a physiological process for implementing this mechanism, and the apparent adherence to this principle may be somewhat coincidental. If minimization of work of breathing was the sole determinant of the magnitude of respiratory frequency and tidal volume, then the lowest frequency of breathing and largest tidal volumes should occur when flow resistance is greatest. In our study, flow resistive work was greatest when the subject respired dense gas through the UBA's. Respiratory frequency was lowest in this condition, but but tidal volumes were not much larger than in the low resistance/N_2-O_2 control condition.

When subjects breathe against imposed resistance in combination, both the inspiratory and expiratory phases of respiration are prolonged (13, 58, 66). The greater the amount of imposed resistance, the longer the prolongation. Positive pressure breathing also prolongs the period required to complete expiration (21). In our study, the time required to complete each respiratory phase was progressively lengthened as resistance increased. In large part it appears that the progressive decreases in respiratory frequency in our study simply reflect the greater time required for each inspiration and expiration to be completed.

The fall in tidal volumes which we observed when subjects breathed sulfur hexafluoride through the UBA's is probably in large part a result of an increase in expiratory reserve volume. Expiratory reserve volume is increased during positive pressure (21) breathing and when subjects are breathing against imposed resistance (13, 66). The subjects in the present study were breathing at high volumes when they respired through the UBA's, and a further increase in expiratory reserve volume may result from the addition of dense gas. Presumably in this situation, the magnitude that tidal volume can increase is limited by the remaining inspiratory reserve volume.

TOTAL INTRINSIC RESPIRATORY WORK

Total intrinsic respiratory work is comprised of several separate, but interacting components. The changes in these components will not be discussed separately, but as they affect the total intrinsic respiratory work at different minute ventilations.

The increase in intrinsic respiratory mechanical work as ventilation increased breathing N_2-O_2 through the low resistance system are comparable to increases previously reported by Milic-Emili, et. al. (44). Elastic and flow resistive work in this condition show a curvilinear response with increased ventilation. This is a result of the larger tidal volumes and greater flow rates during exercise. Negative work increases, but the rate of increase lessens as ventilation rises, indicating that more of the work stored during inspiration is utilized during expiration.

When nitrogen-oxygen is breathed through the MARK VIII, intrinsic respiratory mechanical work again shows a curvilinear response as respiratory minute volume rises. Respiratory mechanical work is greater than in the low resistance N_2-O_2 condition. This is primarily a result of an increase in the elastic work component, and to a lesser extent an increase in negative work. These increases in elastic work were primarily a function of the larger tidal volumes during nitrogen-oxgyen breathing through the MARK VIII. An additional factor which is presumably increasing elastic work is related to the increases in expiratory reserve volume which occur with positive pressure (21) and resistive breathing (13, 66). As resting lung volumes are shifted to higher levels, compliance is decreased and the elastic work is increased. The work expended in overcoming the non-elastic resistance of the lungs and in moving gas in the airways while breathing nitrogen-oxygen with the MARK VIII was the same as in the control condition. This indicates that flow resistance was not appreciably diminished by any increase in airway diameter resulting from the combination of positive pressure and resistive breathing.

The linear response of intrinsic respiratory mechanical work with increasing ventilation while breathing nitrogen-oxygen through the MARK XI combinations is best explained by analyzing the various component responses. Elastic work increased to the same extent, and presumably for the same reasons that it increased with the MARK VIII. There was little difference in the amount of flow resistive work with the MARK XI combinations at low and moderate ventilations compared to the MARK VIII.

At high ventilations, the work expended in overcoming flow resistance with the MARK XI was less than with the MARK VIII. The reason for this decrease is not altogether clear. However, the subjects who used the MARK XI complained that expiratory resistance was greater than with the MARK VIII. Table 10 substantiates this complaint. Additionally, there is reason to believe that the dynamic characteristics of the MARK XI pop-off valve differ from those of the MARK VIII, and the amount of positive pressure breathing with the MARK XI was somewhat greater than with the MARK VIII. This combination of increased expiratory resistance and of increased positive pressure breathing would tend to produce a greater degree of lung distention. The consequence would be to increase airway diameter and diminish intrinsic flow resistive work.

Negative work breathing with the MARK XI was less at high ventilations than with the MARK VIII. This indicates that more of the potential energy obtained during inspiration was utilized in expiration. This lessening of both flow resistance and negative work at ventilations above 25 L/min offsets the increased elastic work. The result is then a linear increase in intrinsic respiratory mechanical work in this condition.

When sulfur hexafluoride-oxygen was breathed through the low resistance system, intrinsic respiratory mechanical work increased curvilinearly as minute ventilation rose. Mechanical work of breathing in this condition was greater than when nitrogen-oxygen was breathed. Elastic work was more than during N_2-O_2 breathing, because of the larger tidal volumes in this condition. Flow resistive work was increased as one would expect when a dense gas is respired. Negative work decreased, reflecting greater utilization of stored elastic energy to expire the sulfur hexafluoride.

Mechanical respiratory work while breathing SF_6-O_2 through the MARK VIII was slightly greater than in the low resistance SF_6-O_2 condition. Greater amounts of elastic and negative work contributed to this increase. Presumably the increases in these components were a result of the same alterations, that occurred when nitrogen-oxygen was breathed with this underwater breathing apparatus. Flow resistive work was slightly less than in the low resistance SF_6-O_2 condition. This most likely results from an increase in airway diameter produced by breathing at high lung volumes.

When sulfur hexafluoride-oxygen was respired through the MARK XI combinations, the response of mechanical work of breathing to increasing ventilation was qualitatively similar to the nitrogen-oxygen conditions with this equipment. Apparently, the same factors were operative during sulfur hexafluoride-oxygen breathing as with nitrogen-oxygen, and as such, warrant no additional comment.

EXTRINSIC RESPIRATORY WORK

The breathing equipment which required the greatest expenditure of external respiratory work with both nitrogen-oxygen and sulfur hexafluoride-oxygen was the MARK XI with the MARK VI mouthpiece. The MARK VIII required only slightly less work.

With nitrogen-oxygen mixtures at sea level, both the MARK VIII and MARK XI combinations are acceptable by Cooper's criteria (19) for extrinsic respiratory work up to ventilations of 50/60 L/min. Breathing a dense gas, equivalent in density to helium-oxygen at 650 feet of sea water, drastically reduces the acceptability of this equipment. The curves for the MARK VIII and MARK XI with the MARK VI mouthpiece indicate that the maximum ventilation attainable by a diver using this equipment to breath a gas which is four times as dense as sea level air is about 45 L/min. At this point, large increases, in external respiratory work rate will theoretically produce only small increases in ventilation. It is interesting that this point coincides with Silverman's (57) standard for the maximum permissible external respiratory work rate for this ventilation.

If Cooper's criteria (19) for maximum external respiratory work are applied, neither the MARK VIII nor the MARK XI combinations would be considered satisfactory at respiratory minute volumes of 40 L/min. The combination of the MARK VIII with the Kirby-Morgan component mouthpiece would theoretically extend acceptability to ventilations of about 45 L/min.

When sulfur hexafluoride was breathed through the MARK VIII and MARK XI combinations, the percentage of extrinsic work which was contributing to the total respiratory work load rapidly increased as ventilation rose. This was generally not the case with nitrogen-oxygen. The implication of this change is that at high flow rates, there is considerable turbulence of the gas within the underwater breathing apparatus. The effect of this turbulence is to markedly increase flow resistance within the equipment.

Work Against Mouthpiece Assemblies:

At low ventilations the contribution to extrinsic respiratory work rate by the MARK VI mouthpiece and the Kirby-Morgan component mouthpiece was very small. At low ventilations, there was little difference between the two mouthpieces. At moderate and high ventilations, the Kirby-Morgan component mouthpiece required appreciably less work than did the MARK VI. This difference is undoubtedly a reflection of the larger orifice sizes of the Kirby-Morgan together with its more pliant check-valves. On the basis of previous study, it can be assumed that the check-valves per se are the largest source of resistance in these assemblies. The incorporation of the Kirby-Morgan components into a mouthpiece assembly slightly increased flow resistance. The extrinsic respiratory work of an unmodified Kirby-Morgan helmet will be somewhat less than that found in this study.

Work Against Carbon Dioxide Absorbent Cannisters:

The carbon dioxide absorbent cannisters contributed the least to external respiratory work with both the MARK VIII and the MARK XI. The work done against the flat-can type cannister of the MARK VIII was slightly greater than that done against the MARK XI cylindrical cannister. This is contrary to the findings of other investigators (27).

Work Against Pop-Off Valves:

The MARK XI pop-off valve required more work than the MARK VIII exhaust valve. The reasons for this difference are not known, but two possibilities can be postulated. The first is that there may be a difference in the effective orifice size for gas flow between the two valves. The other possibility is that there may be a greater amount of loading when the MARK XI valve is open in dynamic conditions than with the MARK VIII valve.

Wasted Work:

In this study wasted work is defined as work not accounted for in gas transport through the underwater breathing apparatus. In large part, wasted work, probably represents work done against elastic resistance whose potential energy is not returned to the system. At low ventilations, wasted work accounted for the major portion of extrinsic respiratory work. At moderate and high ventilations with the MARK VIII wasted work was percentage-wise a small contributor to the total extrinsic respiratory work rate. This finding concurs with Cooper's work (19). With the MARK XI UBA, wasted work was appreciably greater than with the MARK VIII. The reason for this difference is not clear.

TOTAL RESPIRATORY WORK

With both nitrogen-oxygen and sulfur hexafluoride-oxygen mixtures, the expenditure of total respiratory work was least with the Kirby-Morgan component mouthpiece. From this standpoint, this underwater breathing apparatus was the most acceptable equipment combination which was tested. At ventilations of 33 L/min. and above, this UBA is not satisfactory for use with dense gas as the total respiratory work expenditure is too great.

The expenditure of large amounts of total respiratory work is required to breathe dense gas with the MARK VIII and the MARK XI with the MARK VI mouthpiece. For this reason these UBA's are not satisfactory as breathing equipment with dense gas at ventilations above 25 L/min. The theoretical total respiratory work - ventilation curve for the MARK VIII with the Kirby-Morgan component mouthpiece implies that the respiratory impedance with this combination would be less than that of any equipment combination which was tested in this study (Figure 43).

CONCLUSIONS

On the basis of this study it is apparent that the MARK VIII UBA and the MARK XI UBA with the MARK VI mouthpiece and with the Kirby-Morgan clamshell helmet are unacceptable for use by divers doing hard work and breathing dense gas. Subjectively, this equipment was disliked and drew severe complaints under these conditions.

During heavy work breathing dense gas through these underwater breathing apparatus, an oxygen debt was contracted. Hypoventilation and carbon dioxide retention were profound and potentially dangerous. Mechanical work of breathing was increased to an unacceptable level. These underwater breathing apparatus fail to meet standards for equipment breathing resistance that have been proposed in the past (Table 10 and Figure 36).

Physiological embarrassment was slightly less with the MARK XI with the Kirby-Morgan than with the other two UBA combinations that were tested, but was still considerable. It is concluded that these diving apparatus cannot satisfy the ventilatory requirements of a diver breathing dense gas during heavy work.

RECOMMENDATIONS

Tentative Standards for Resistance in SCUBA:

The only means by which the increases in intrinsic respiratory impedance that a diver experiences while breathing a dense gas can be minimized is by use of gases such as helium. However, on the basis of this study, it is apparent that most of the breathing impedance which a diver encounters is man-made and resides in the equipment rather than in the man.

Any standards that are proposed for breathing resistance in SCUBA must necessarily be somewhat arbitrary. Because of the interaction of hydrostatic pressure imbalances with equipment resistance, the increases in respiratory impedance which a diver encounters can be severe. For this reason, specifications must be proposed for the magnitude of positive and negative pressure breathing, as well as for equipment resistance.

As was previously discussed, in aviation the maximum for continuous positive pressure breathing is = 20 cm H_2O. Even at this pressure profound physiological alterations and syncopal episodes may occur. A diver may of necessity have to work in a single position for long periods. As a consequence he would be exposed to long periods of positive or negative pressure breathing. For this reason, and because of the interaction of pressure breathing with equipment resistance, the authors recommend that a diver should never have to positive or negative pressure breathe at pressures greater than

15 cm H_2O. The optimum situation would limit hydrostatic pressure to + or - 75 cm H_2O.

Silverman (57) stated that at a work load of 830 Kg-M/min, inspiratory resistance would not exceed 82 mm H_2O and expiratory resistance be no greater than 53 mm H_2O. At a work load of 1107 Kg-M/min the maximum tolerable resistance was 64 mm H_2O on the inspiratory side and 41 mm H_2O on the expiratory side. If these standards are applied to the diving situation, the effect of increased gas density must be considered. Therefore, the maximum resistance for gas flow in diving equipment could not exceed these standards at a flow rate of 85 L/min with the densest gas mixture that may possibly be used with the equipment.

Silverman's (57) standards do not consider the concurrent presence of either positive or negative pressure. Therefore, it is desirable to reduce these standards for diving equipment. The maximum external work load that a diver is likely to encounter is about 1000 Kg-M/min. The authors propose that at this work load, inspiratory resistance should not exceed 60 mm H_2O and that expiratory resistance be no greater than 40 mm H_2O. These resistances are of course at a flow rate of 85 L/min with the maximum density gas.

Standards for breathing impedance which are expressed in terms of total external respiratory work take into consideration both equipment flow resistance and hydrostatic pressure. Silverman's (57) standard as modified by Cooper (18) probably represents as valid a standard for maximum permissible breathing impedance as can be postulated in the present state of knowledge. On this basis the authors recommend that the total external respiratory work rate should never be greater than 0.6% of the external work load. During heavy work (1000 Kg-M/min) this would amount to 6 KgM/min.

It should be noted that subjects whose external respiratory work rate is this high experience discomfort and physiological embarrassment. There is considerable evidence to condemn as unsafe an apparatus which does not meet this standard. Additionally, there is considerable evidence to support a reduction of external respiratory work rate well below this standard.

Proposed Testing Methods to Determine Breathing Impedance of Underwater Breathing Apparatus:

The authors recommend that breathing impedance be determined for all Underwater Breathing Apparatus. Equipment breathing impedance should be expressed in terms of total external respiratory work rate.

Little equipment is required to determine external respiratory work rate. A bicycle ergometer or equivalent means of regulating external work load is needed. Measurements of ventilatory flow rates can be obtained by a pneumotachometer. Mouthpiece to ambient differential pressure can be measured with a differential pressure transducer. A gas such as sulfur hexafluoride should be utilized, and its density adjusted for the maximum depth to which the equipment is to be certified.

Only two subjects are required. These subjects should be studied at rest and while exercising at work loads of

500 and 1000 Kg-M/min. If a semi-closed UBA is being studied, then the pop-off valve should be set to relieve at +5 cm H_2O. A plot of respiratory minute volume to external respiratory work rate can then be constructed as in Figure 36.

A more detailed description of the experimental technique and method for computing external respiratory work rate is given in the METHODS AND MATERIALS Section of this report.

Future Studies:

Future study should be directed towards a determination of the breathing impedance of the submerged diver. The bio-instrumentation necessary to conduct a study of this sort will have to be developed. Immersion will alter to an undetermined degree the respiratory impedance of both the diver and his underwater breathing apparatus. It is anticipated that the alterations induced by immersion will only intensify the deleterious physiological changes which we observed in a "dry" environment.

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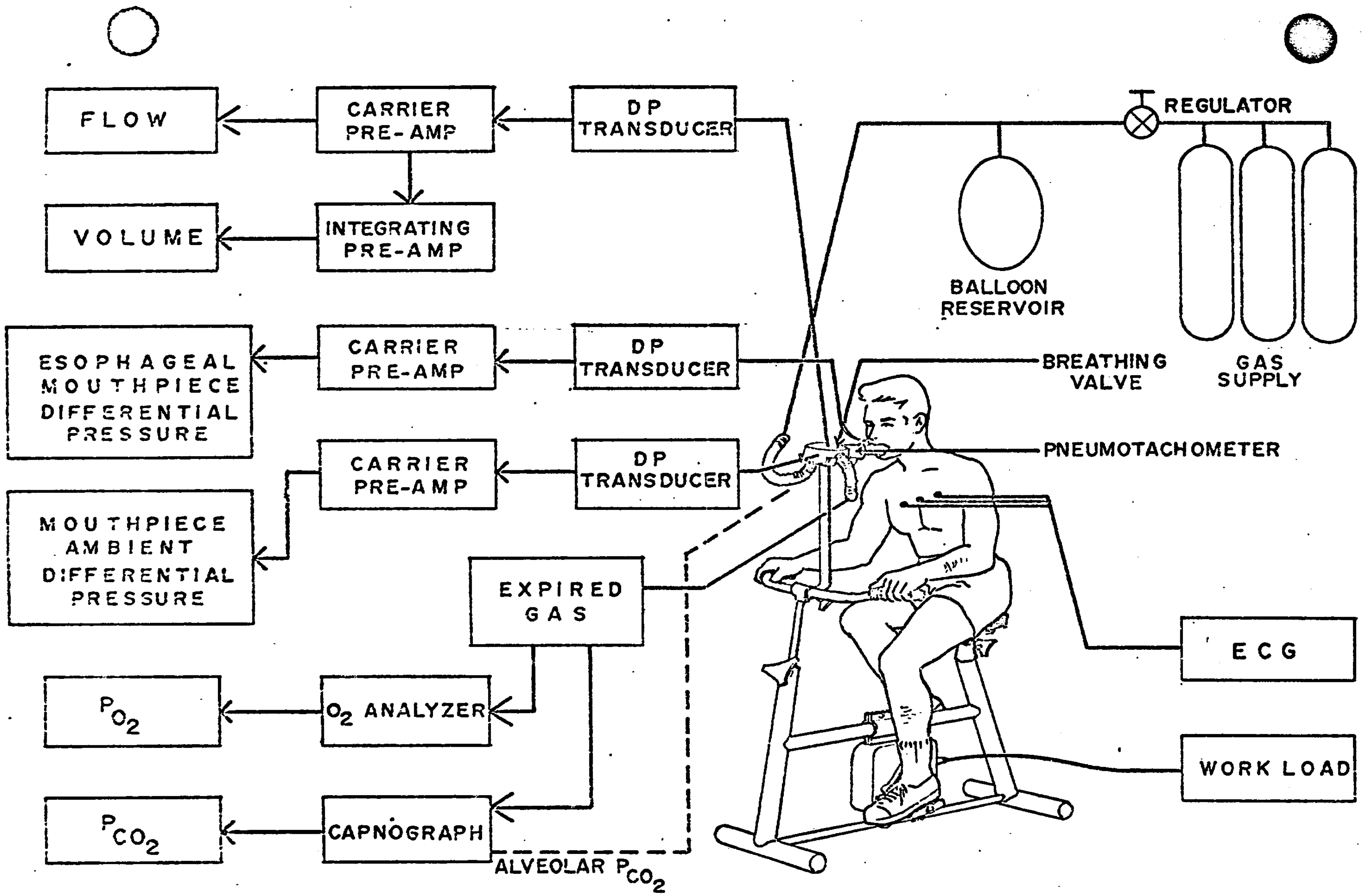

FIG. 1
SCHEMATIC DIAGRAM OF LOW RESISTANCE EXPERIMENTAL SET-UP

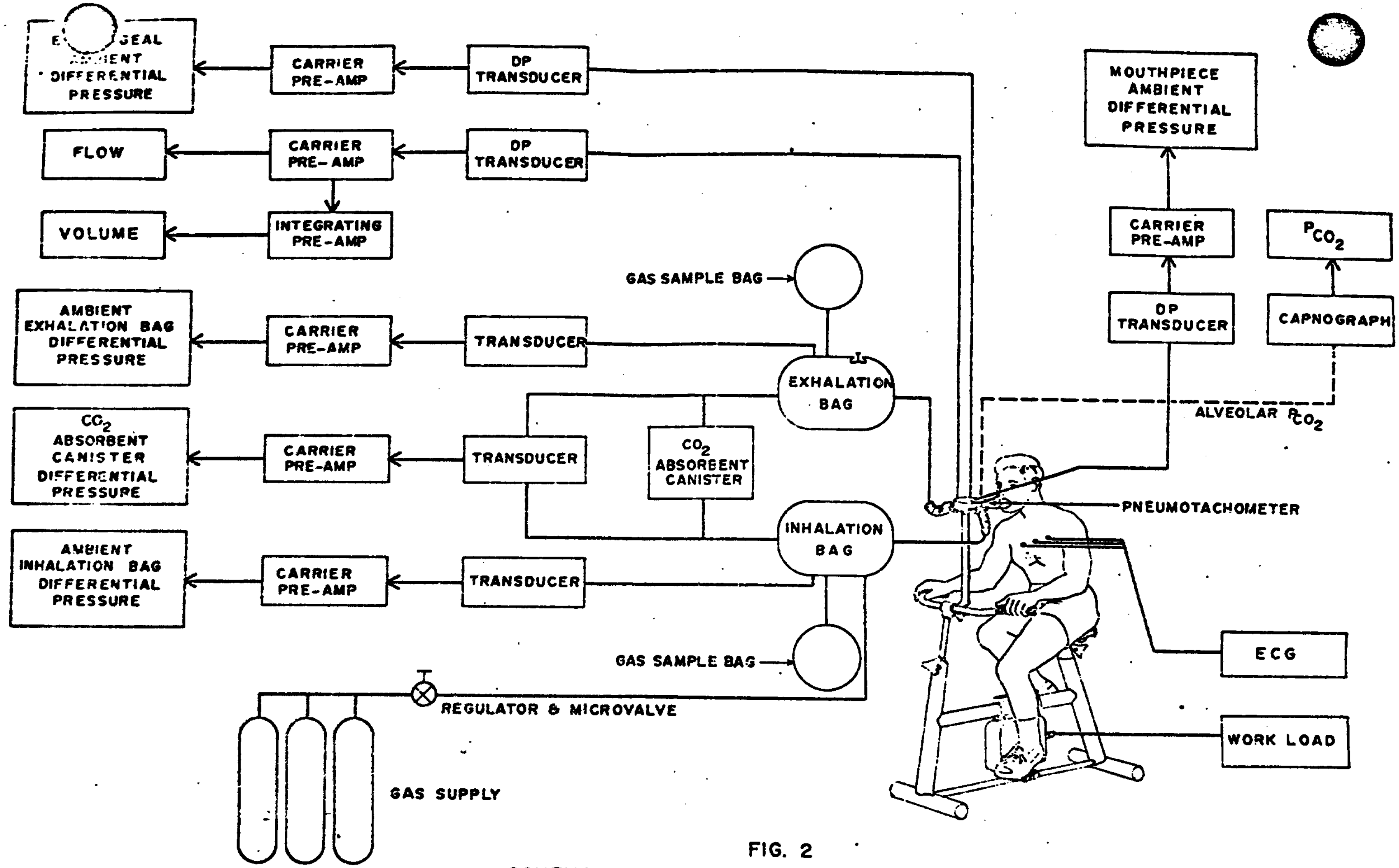

FIG. 2

SCHEMATIC DIAGRAM OF MARK VIII AND MARK XI EXPERIMENTAL SET-UPS

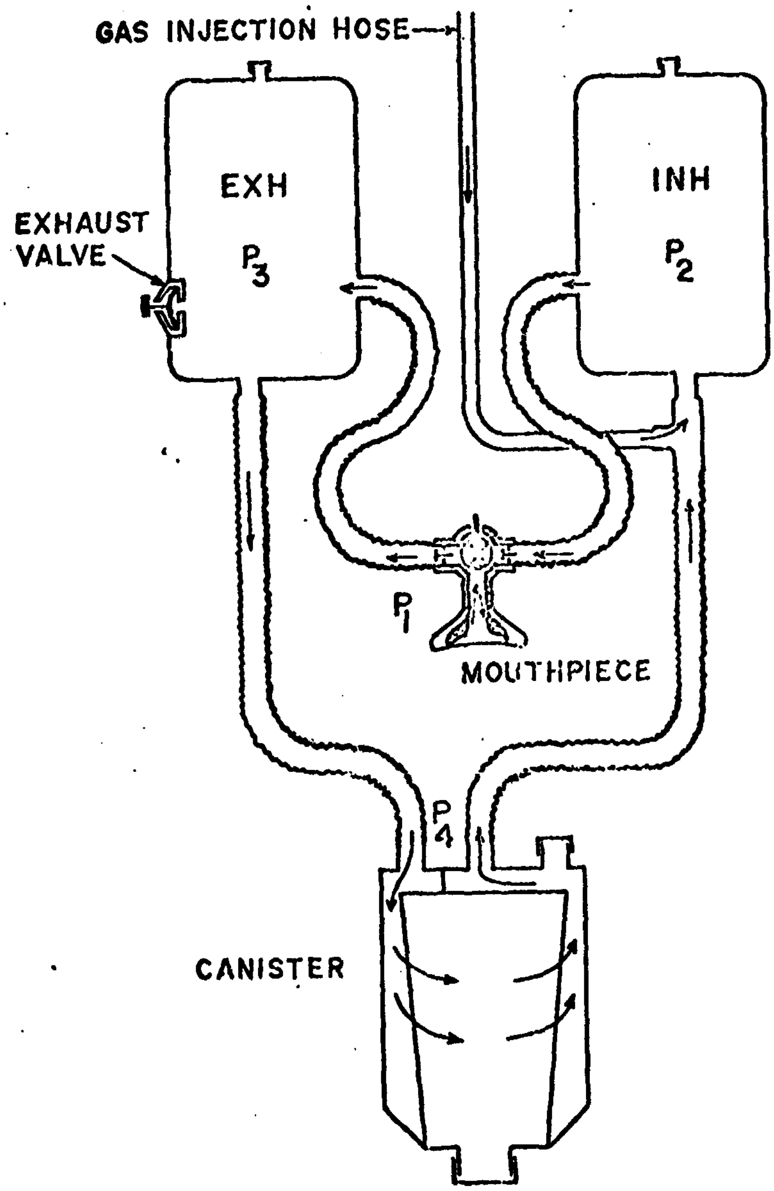

FIG. 3

BREATHING CIRCUIT OF THE MARK VIII, MOD I UBA

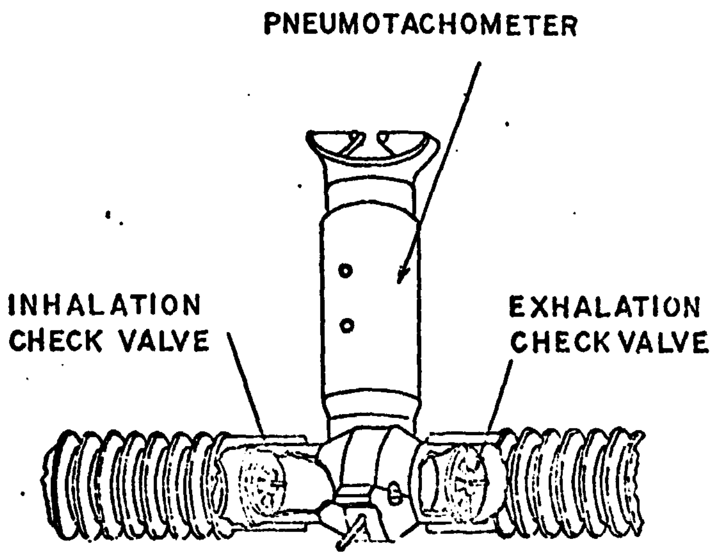

FIG. 4

MARK VI MOUTHPIECE UNIT
AND PNEUMOTACHOMETER

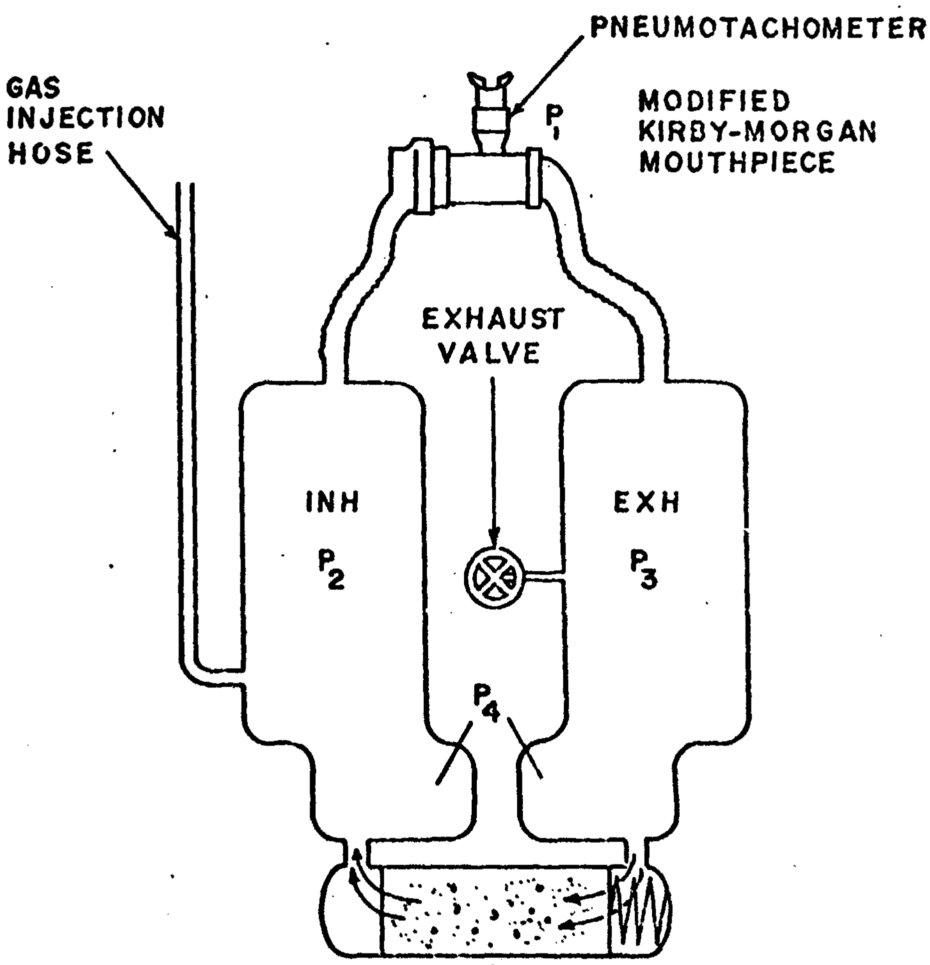

FIG. 5

BREATHING CIRCUIT OF MARK XI UBA

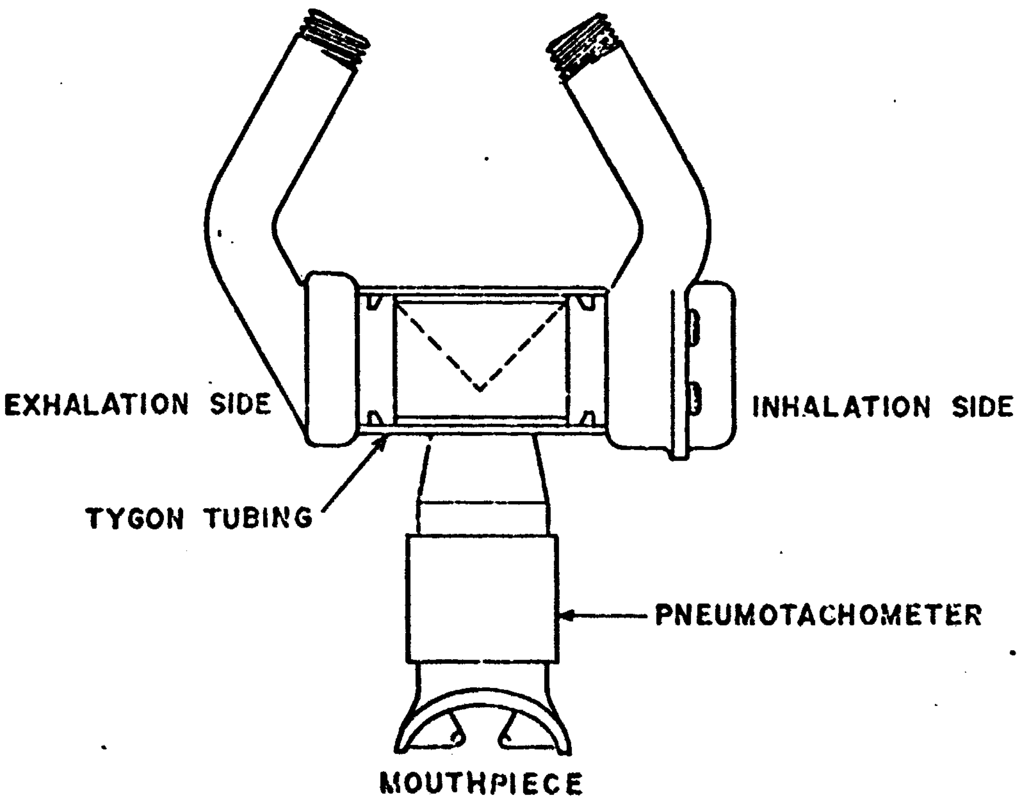

FIG. 6

KIRBY-MORGAN MOUTHPIECE ASSEMBLY

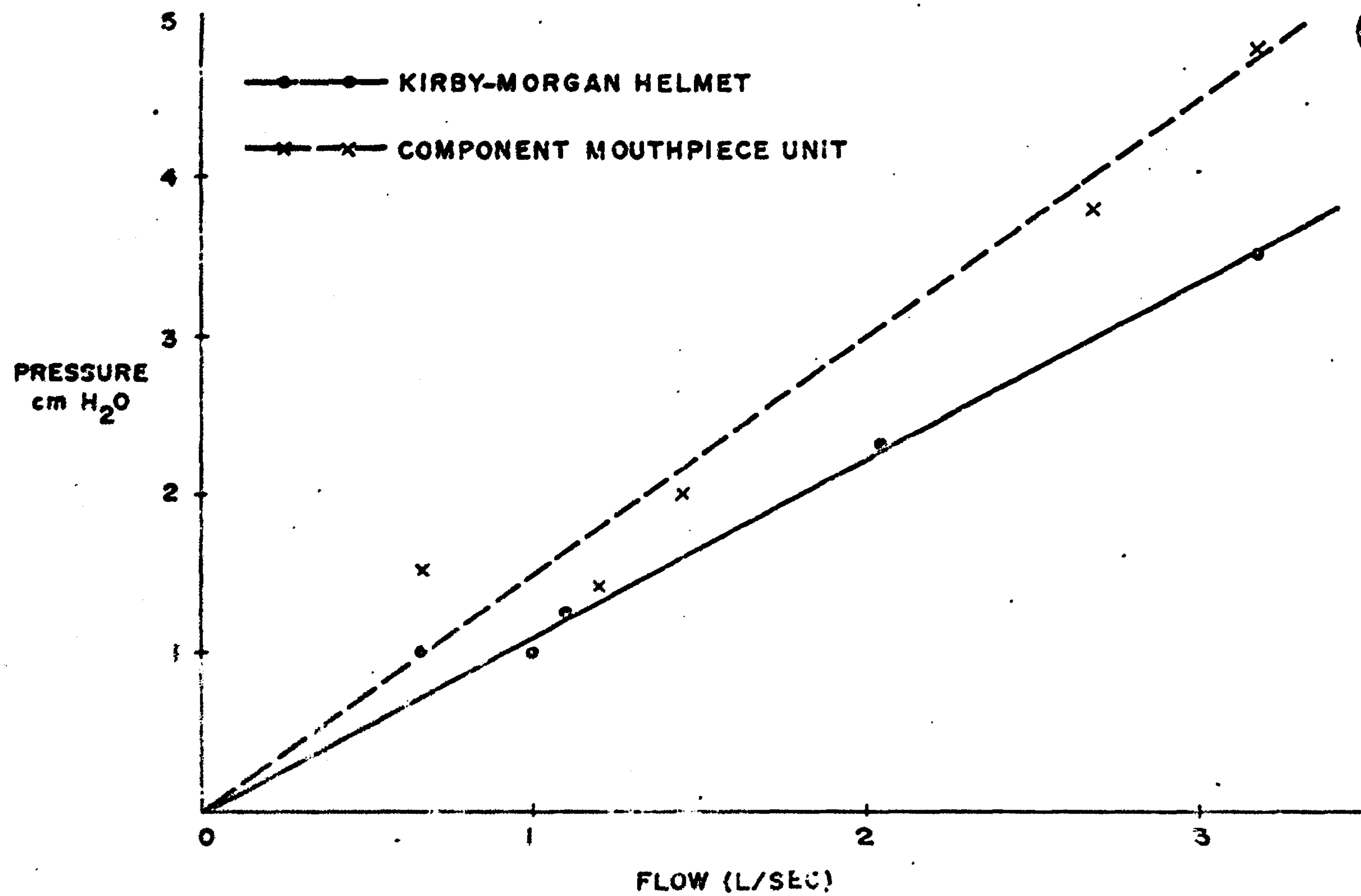

FIG. 7 - INHALATION FLOW RESISTANCE OF THE KIRBY-MORGAN CLAMSHELL HELMET AND OF THE K-M COMPONENT MOUTHPIECE ASSEMBLY.

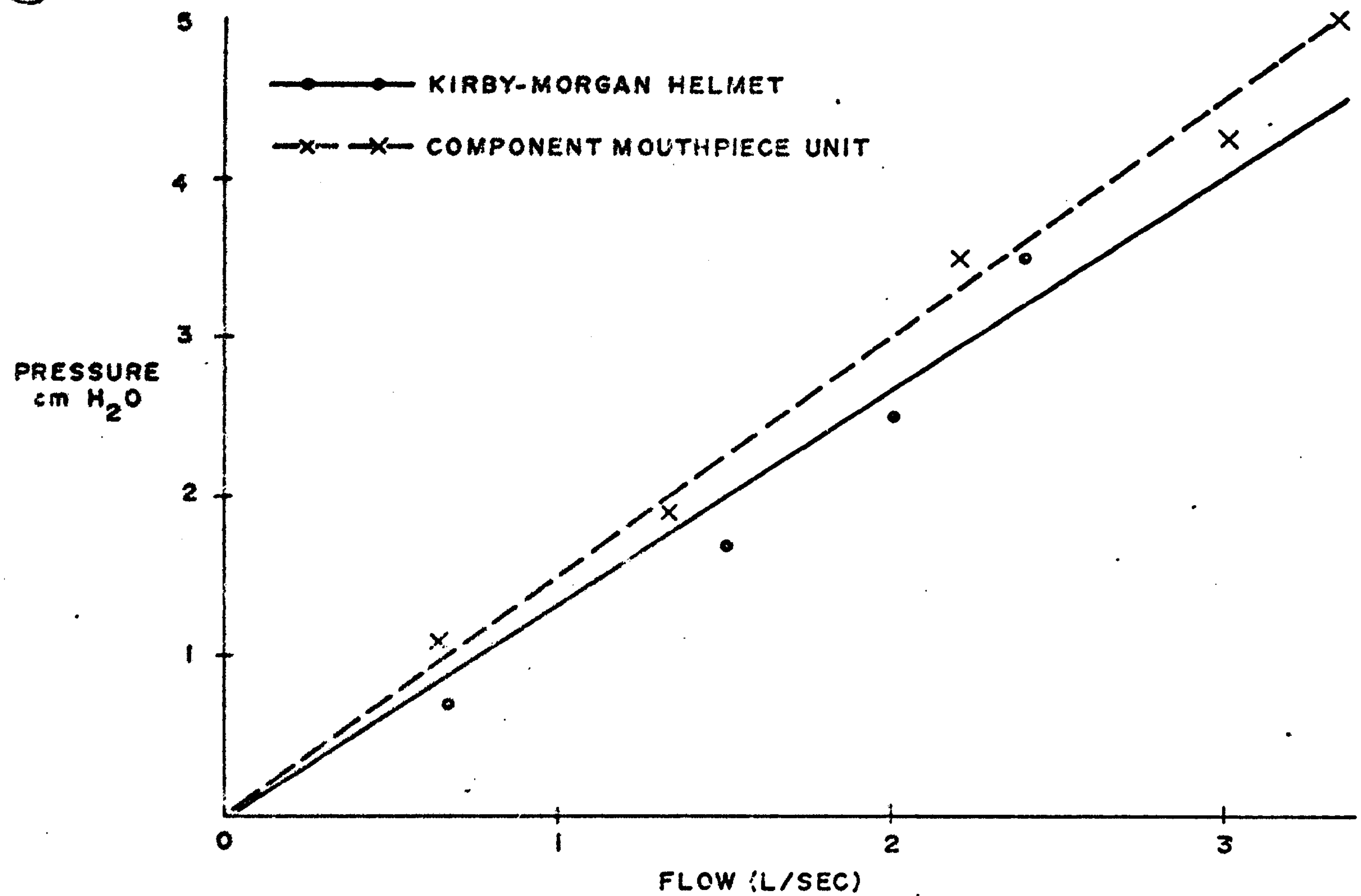

FIG. 8 - EXHALATION FLOW RESISTANCE OF THE KIRBY-MORGAN CLAMSHELL HELMET AND OF THE K-M COMPONENT MOUTHPIECE ASSEMBLY.

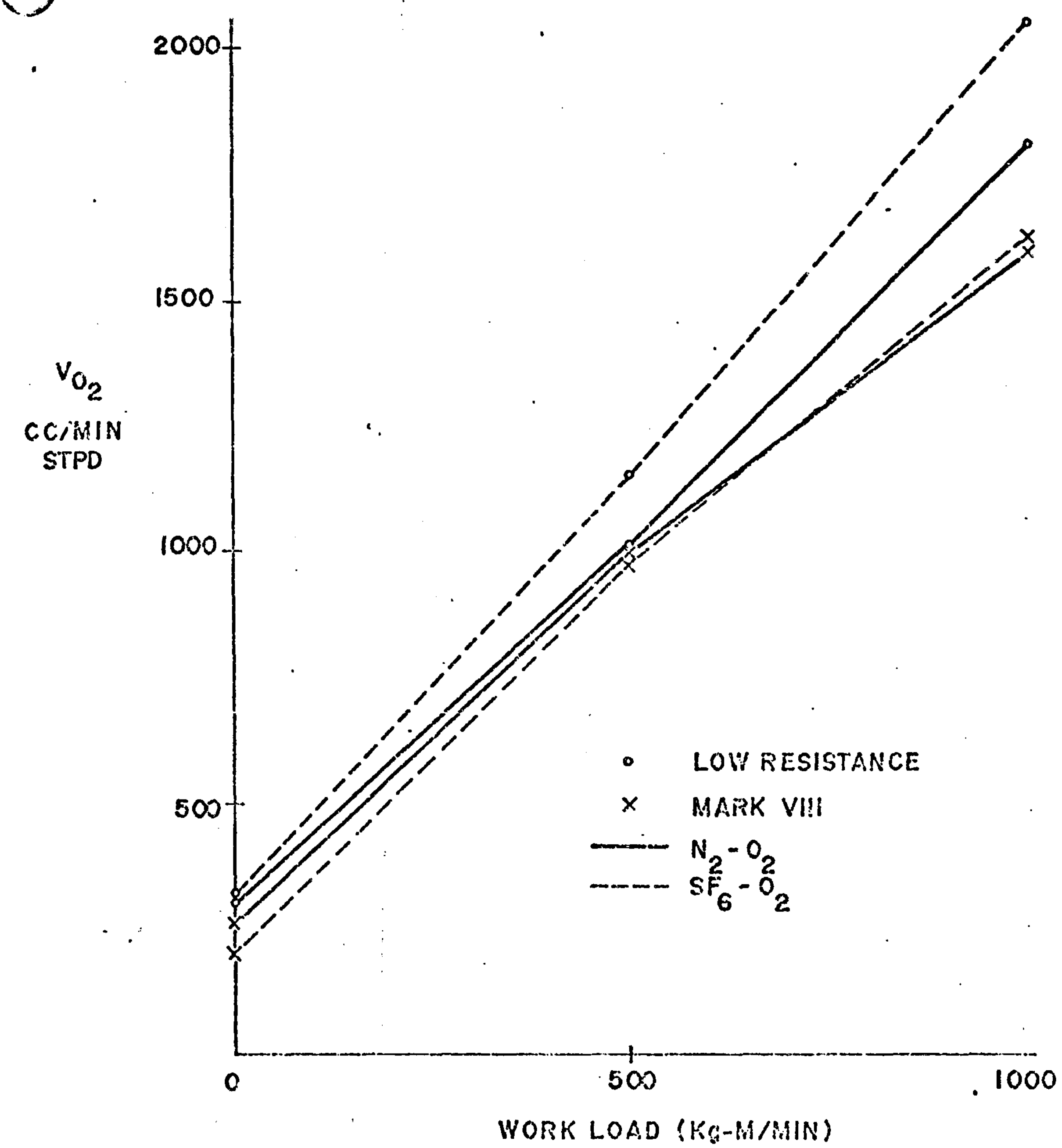

FIG. 9 - OXYGEN UPTAKE OF SIX SUBJECTS AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THE MARK VIII.

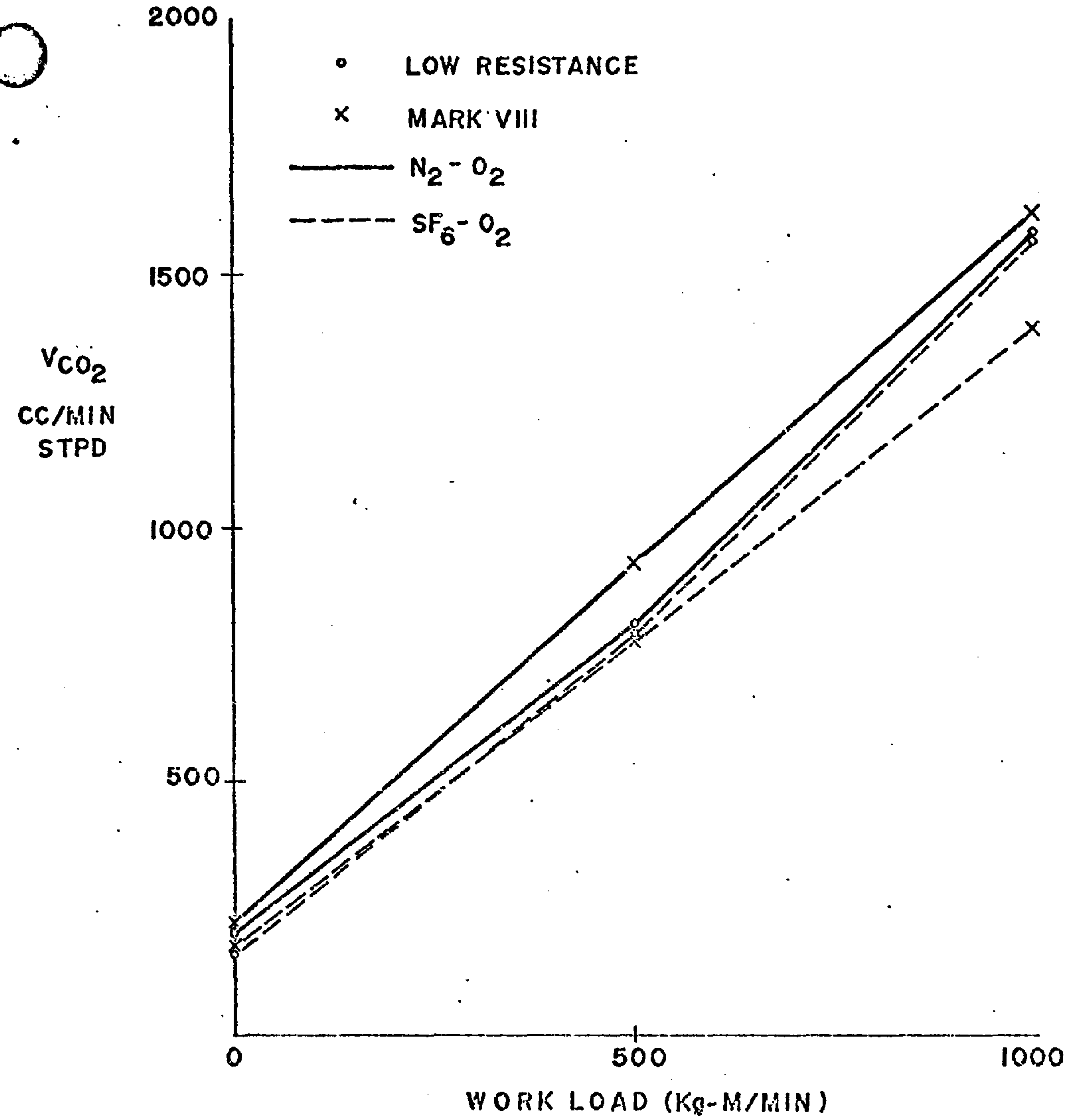

FIG. 10 - CARBON DIOXIDE PRODUCTION OF SIX SUBJECTS AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THE MARK VIII.

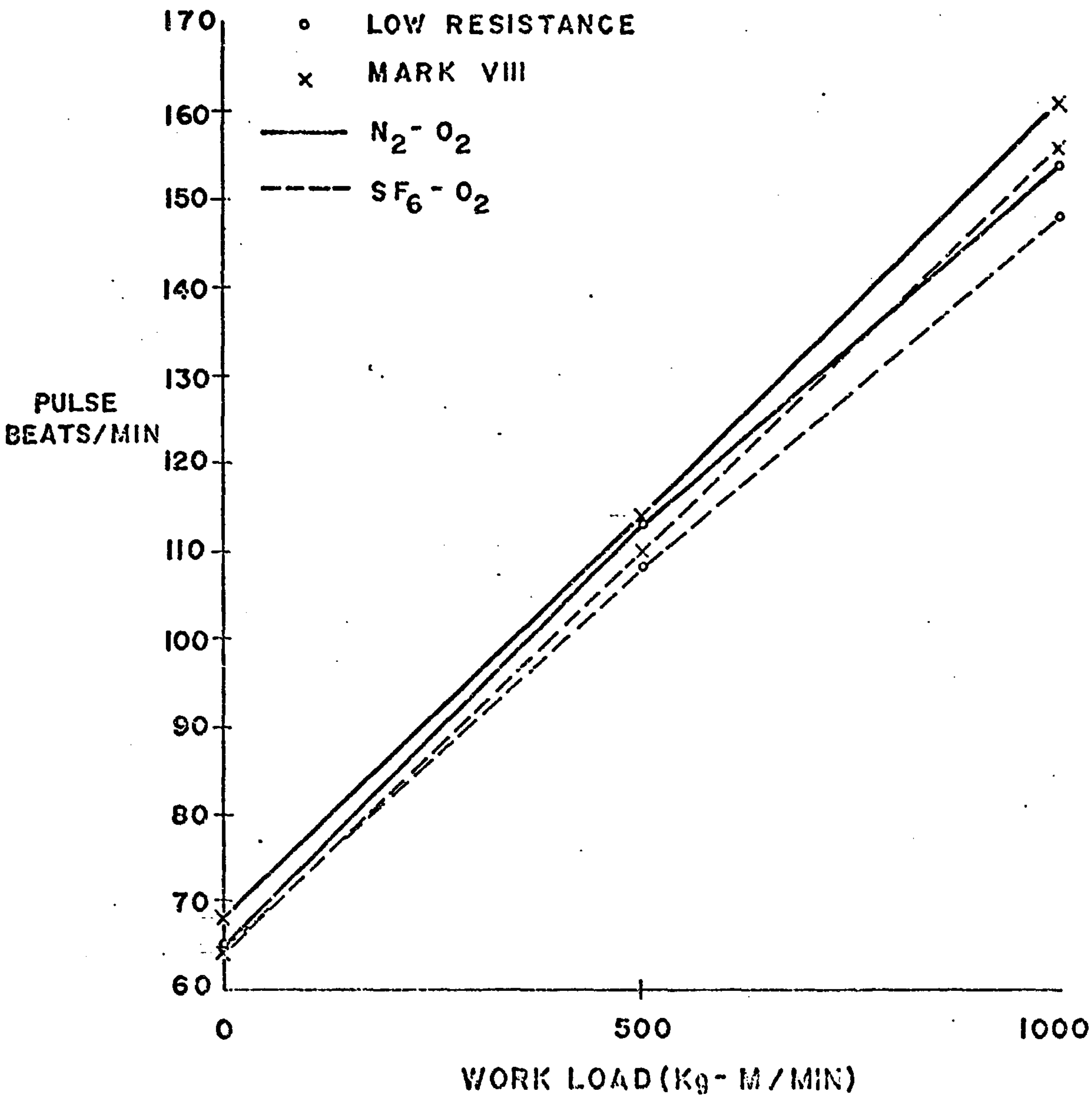

FIG. 11 - PULSE OF SIX SUBJECTS AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THROUGH THE MARK VIII

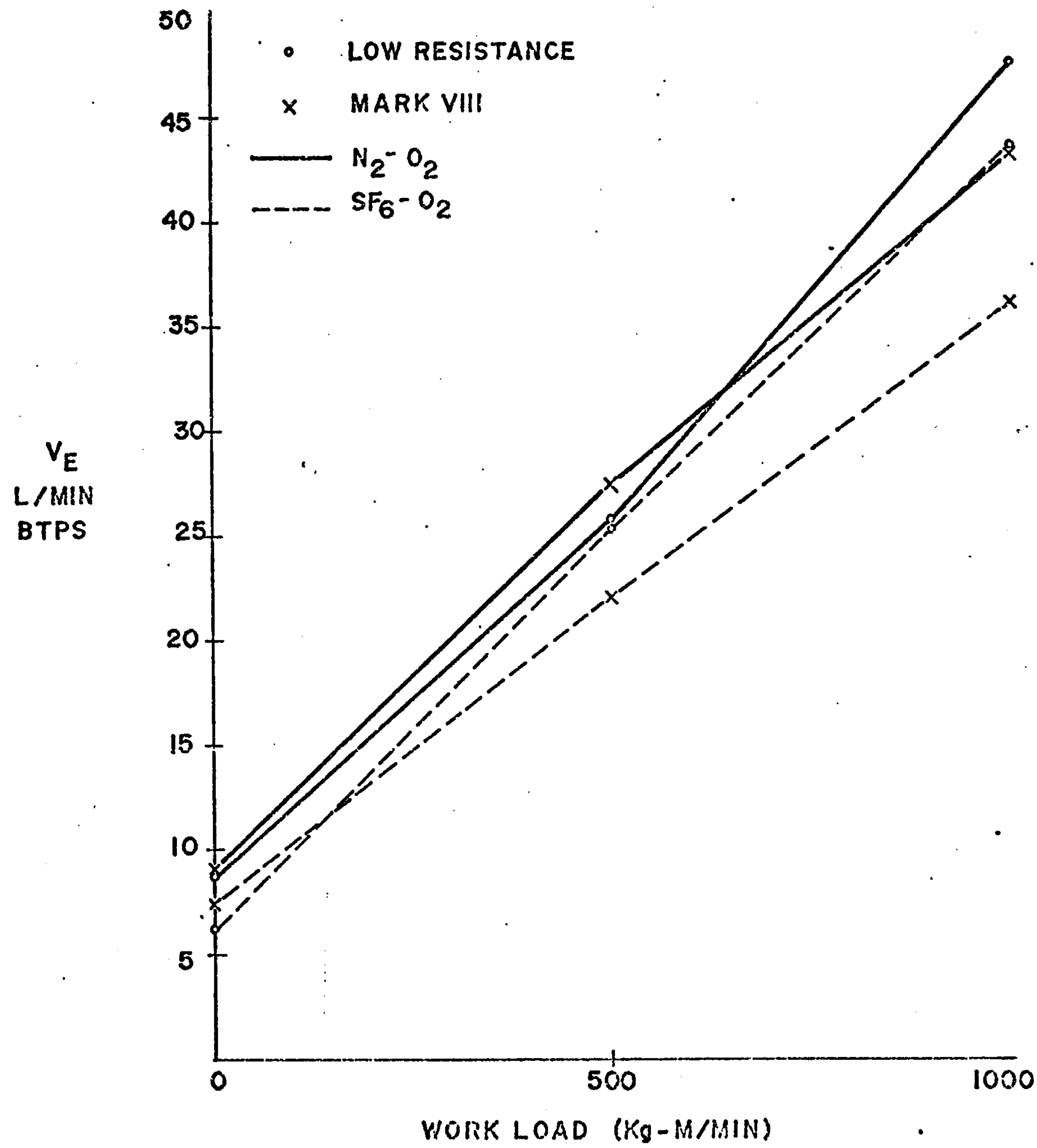

FIG. 12 - RESPIRATORY MINUTE VOLUME OF SIX SUBJECTS AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THE MARK VIII.

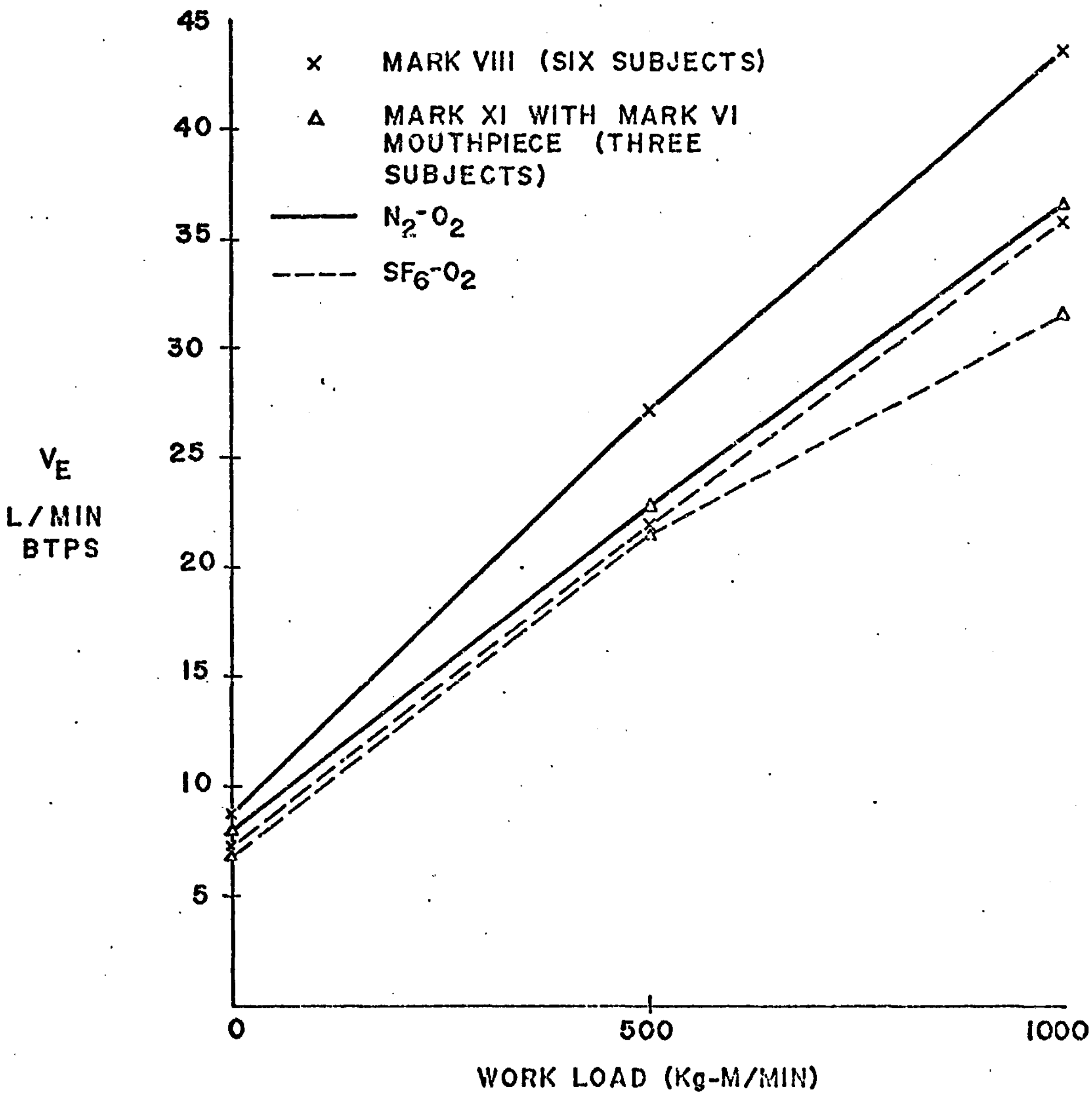

FIG. 13 - RESPIRATORY MINUTE VOLUME AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE MARK VIII UBA AND THE MARK XI WITH MARK VI MOUTHPIECE.

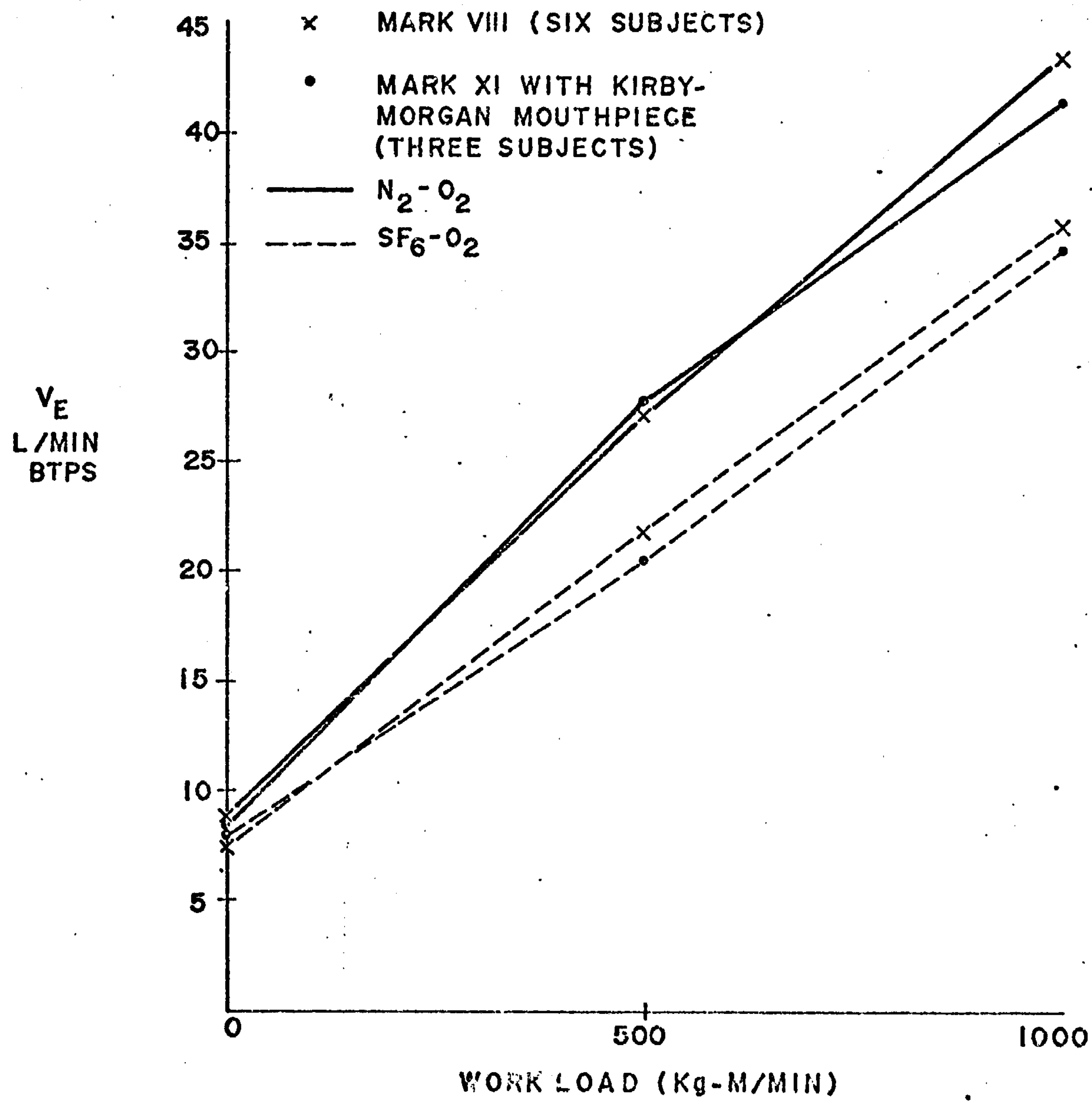

FIG. 14 - RESPIRATORY MINUTE VOLUME AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE MARK VIII UBA AND MARK XI WITH KIRBY-MORGAN COMPONENT MOUTHPIECE.

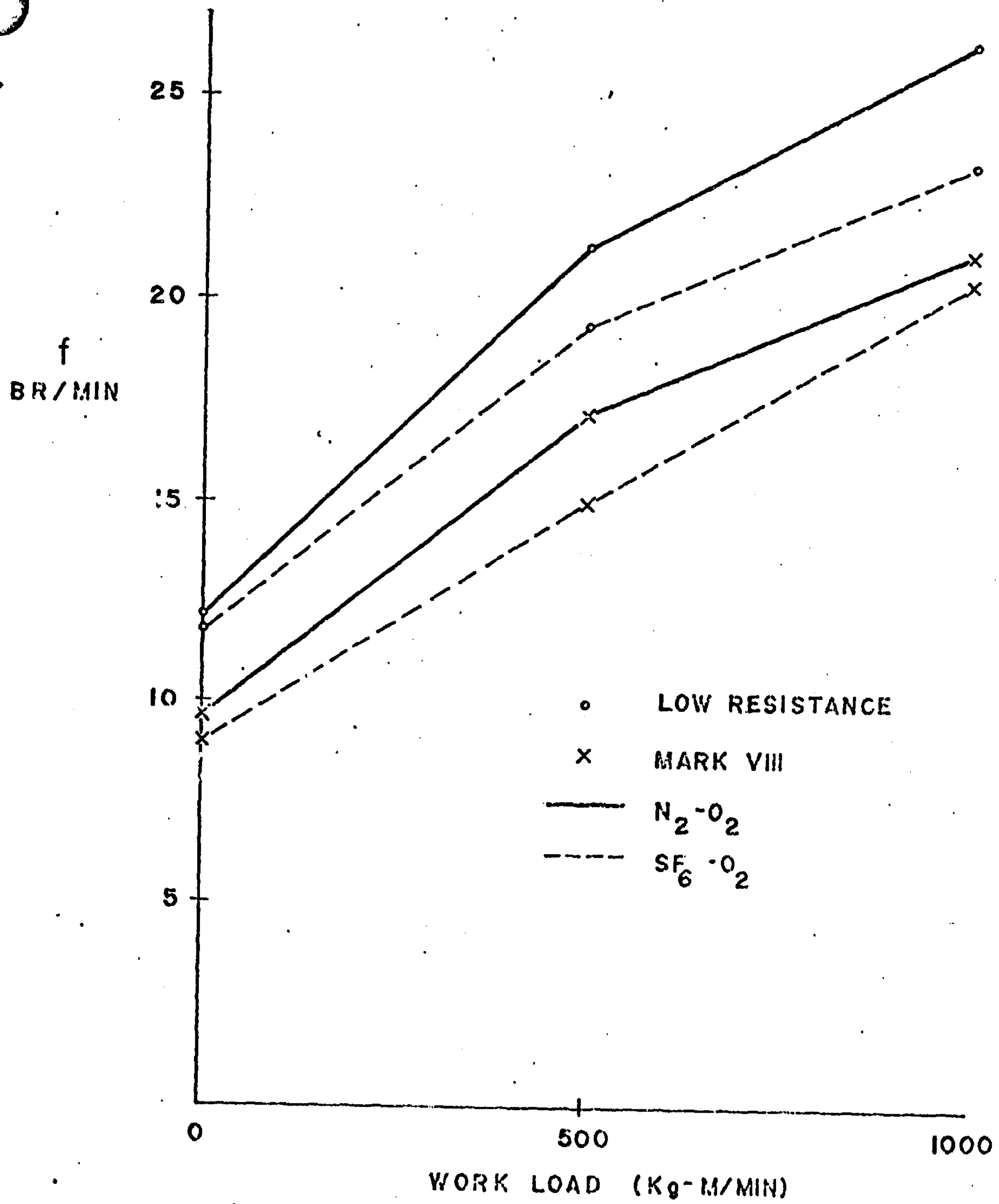

FIG. 15 - RESPIRATORY FREQUENCY OF SIX SUBJECTS AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THROUGH THE MARK VIII

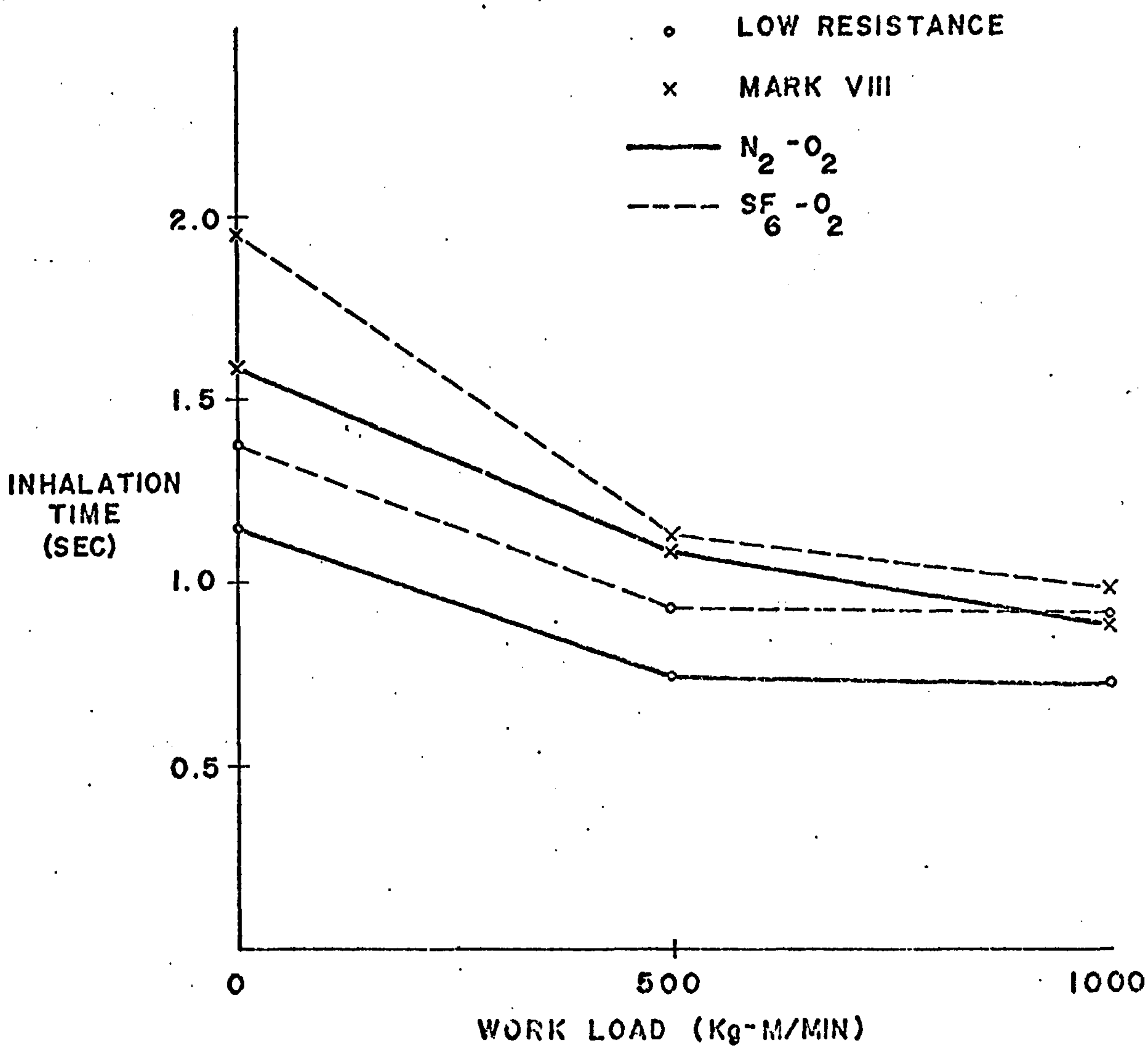

FIG. 16 - MEAN INHALATION TIME OF FOUR SUBJECTS AT REST AND DURING EXERCISE WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THROUGH THE MARK VIII

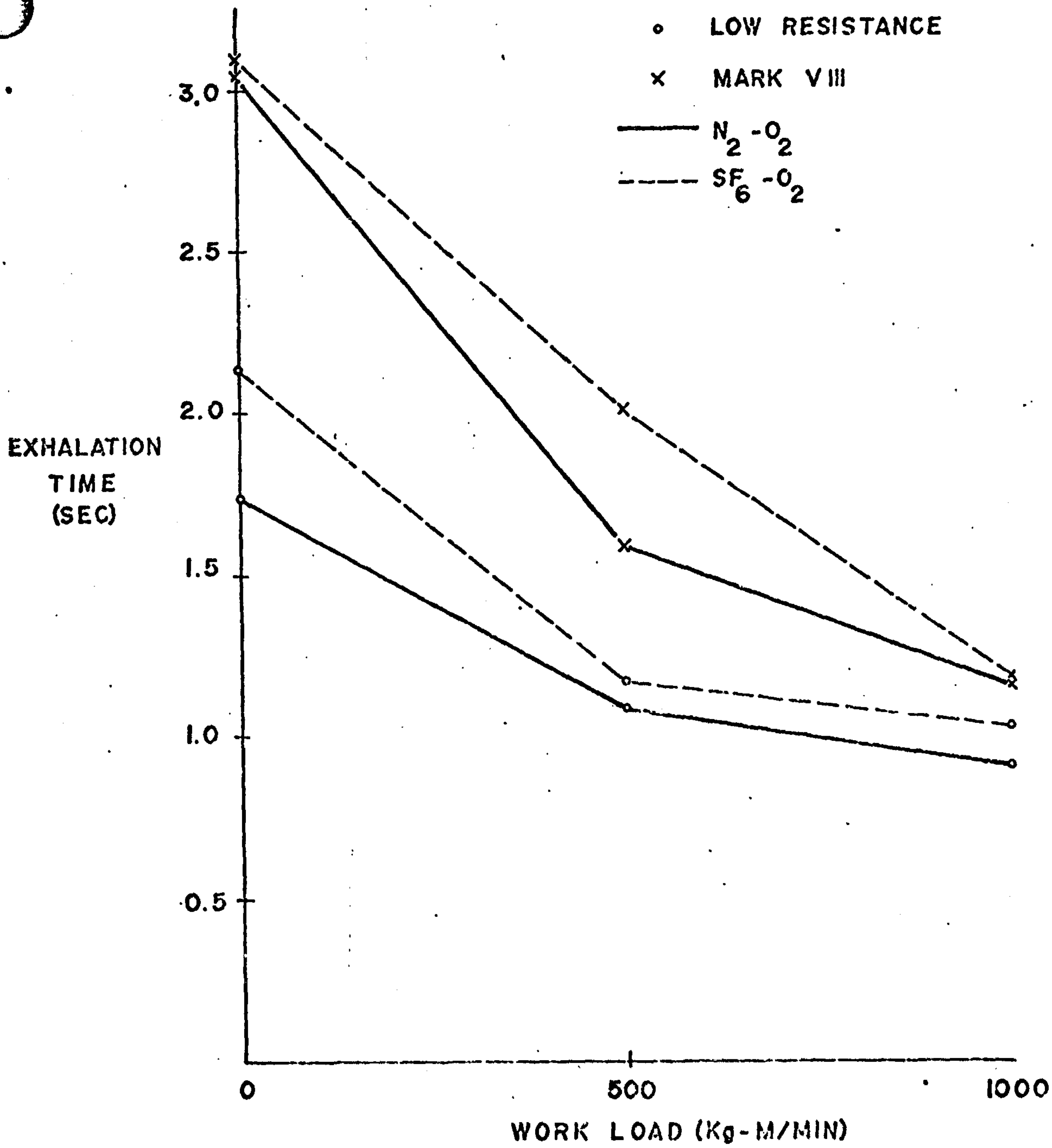

FIG. 17 - MEAN EXHALATION TIME OF FOUR SUBJECTS AT REST AND DURING EXERCISE WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THROUGH THE MARK VIII

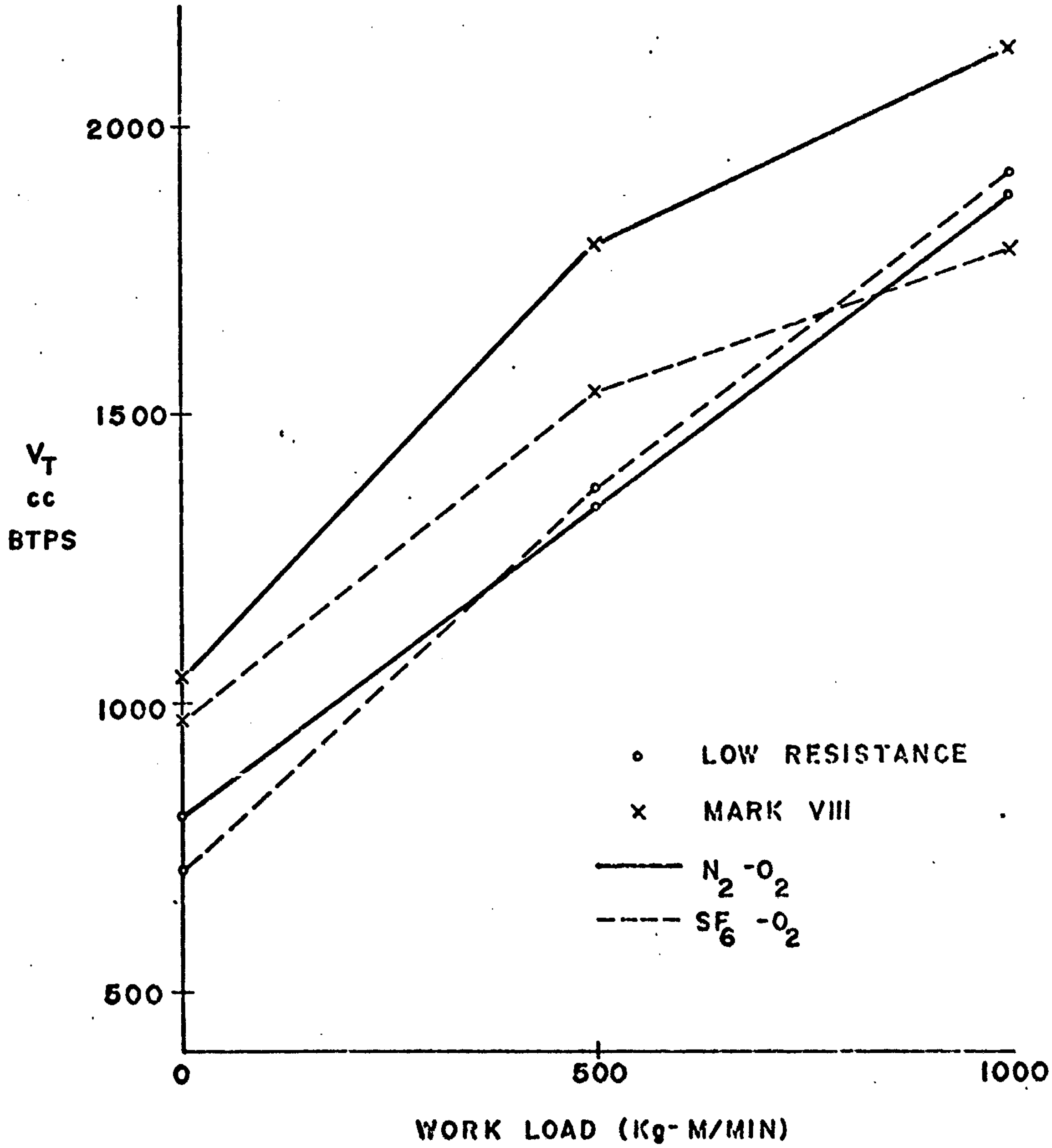

FIG. 18 - TIDAL VOLUME OF SIX SUBJECTS AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THROUGH THE MARK VIII

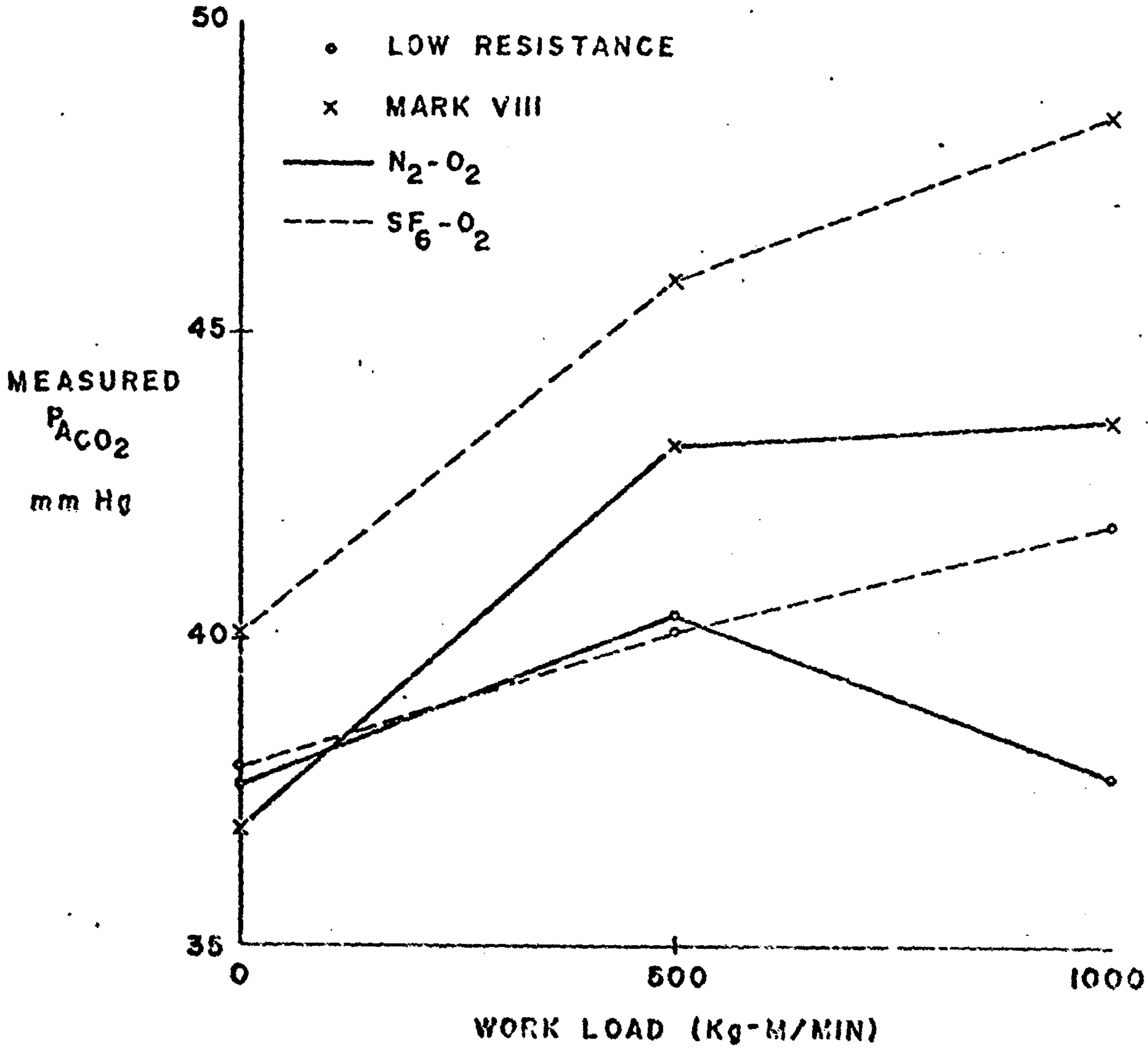

FIG. 19 - ALVEOLAR CO_2 TENSIONS OF SIX SUBJECTS AT REST AND DURING EXERCISE WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM AND THE MARK VIII

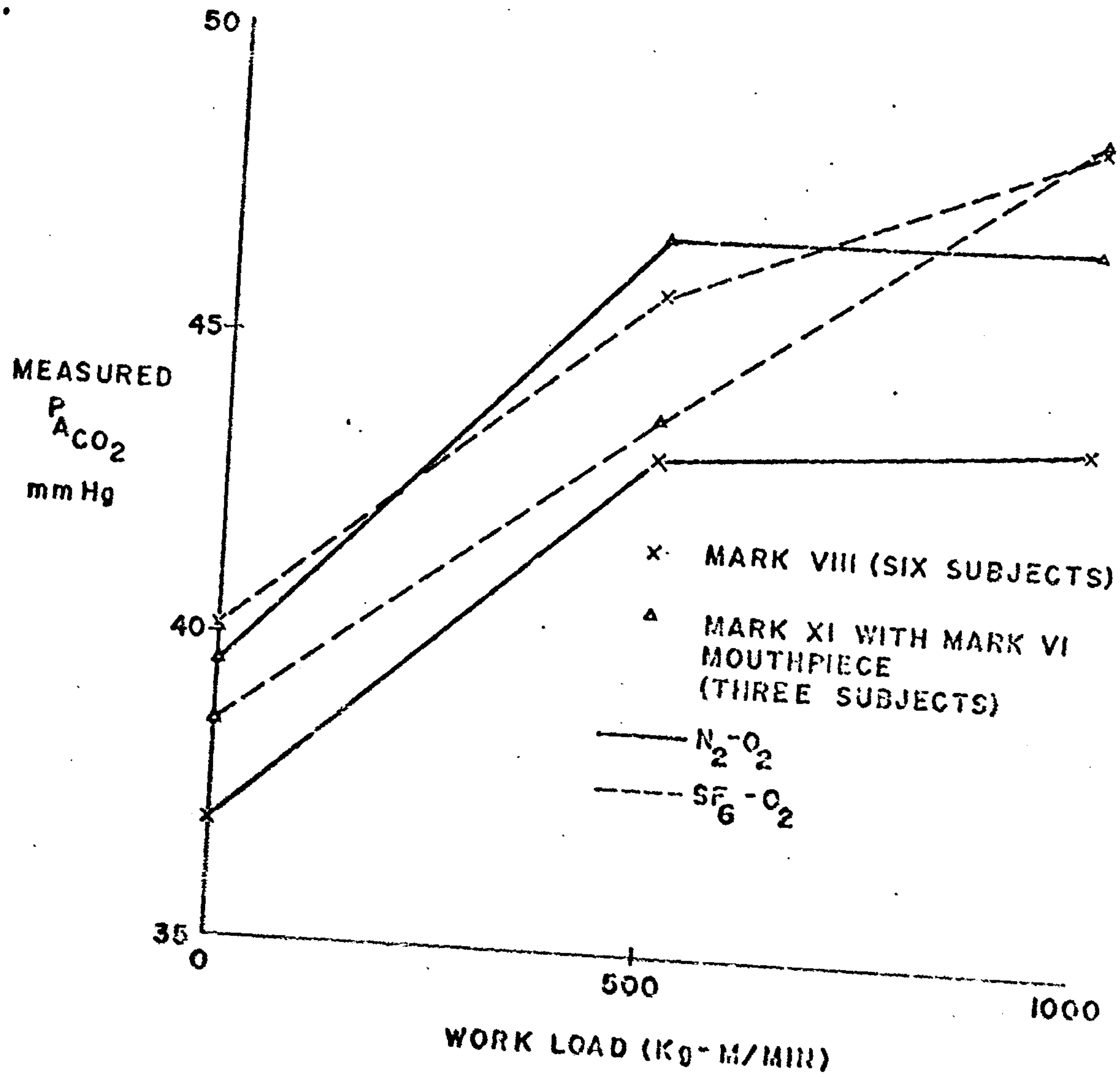

FIG. 20 - ALVEOLAR CO_2 TENSIONS AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6-O_2 THROUGH THE MARK VIII AND MARK XI WITH THE MARK VI MOUTHPIECE

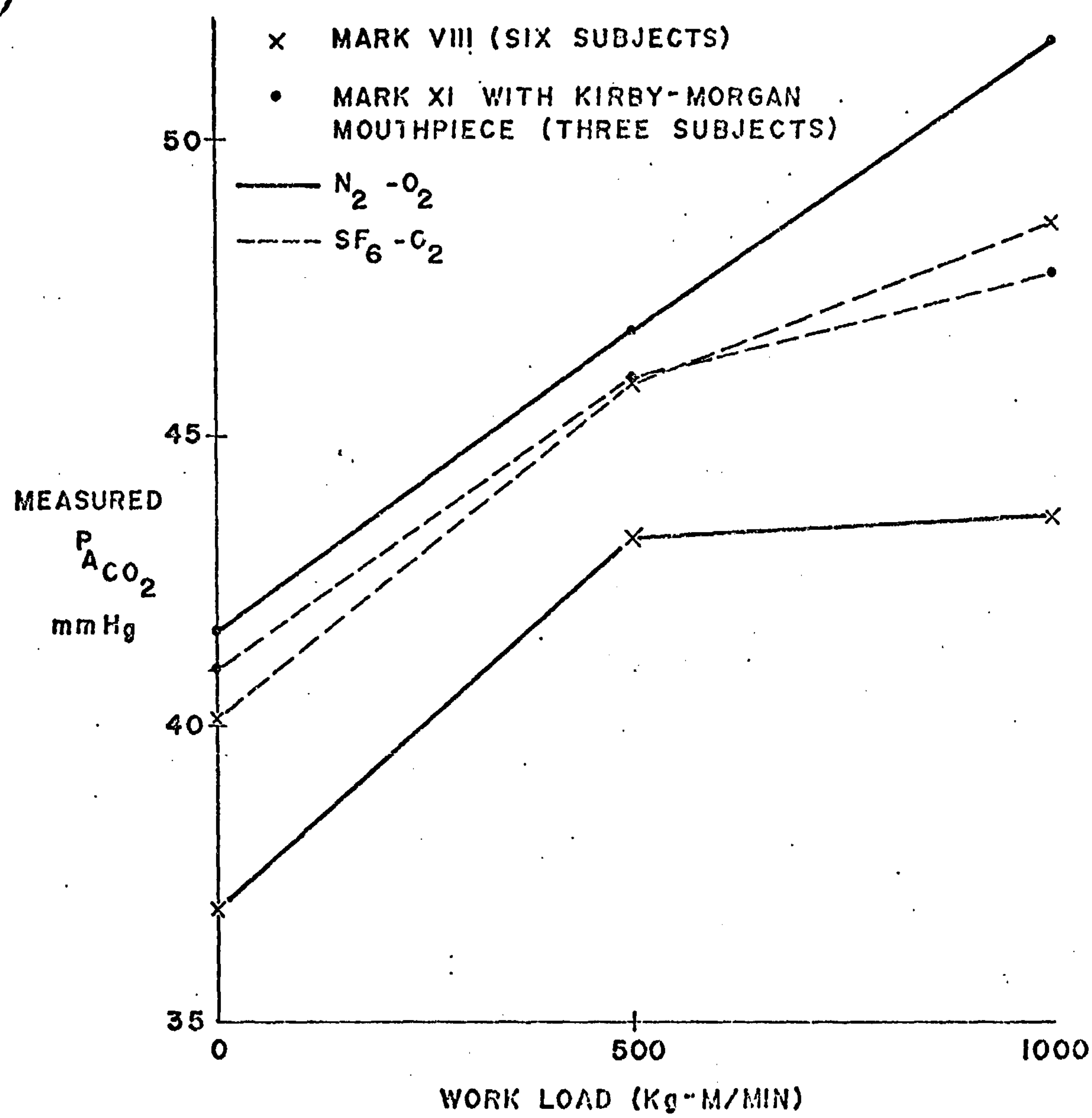

FIG. 21 - ALVEOLAR CO_2 TENSIONS AT REST AND DURING EXERCISE IN RELATION TO WORK LOAD WHILE BREATHING N_2-O_2 AND SF_6 -O_2 THROUGH THE MARK VIII UBA AND MARK XI WITH THE KIRBY-MORGAN MOUTHPICE

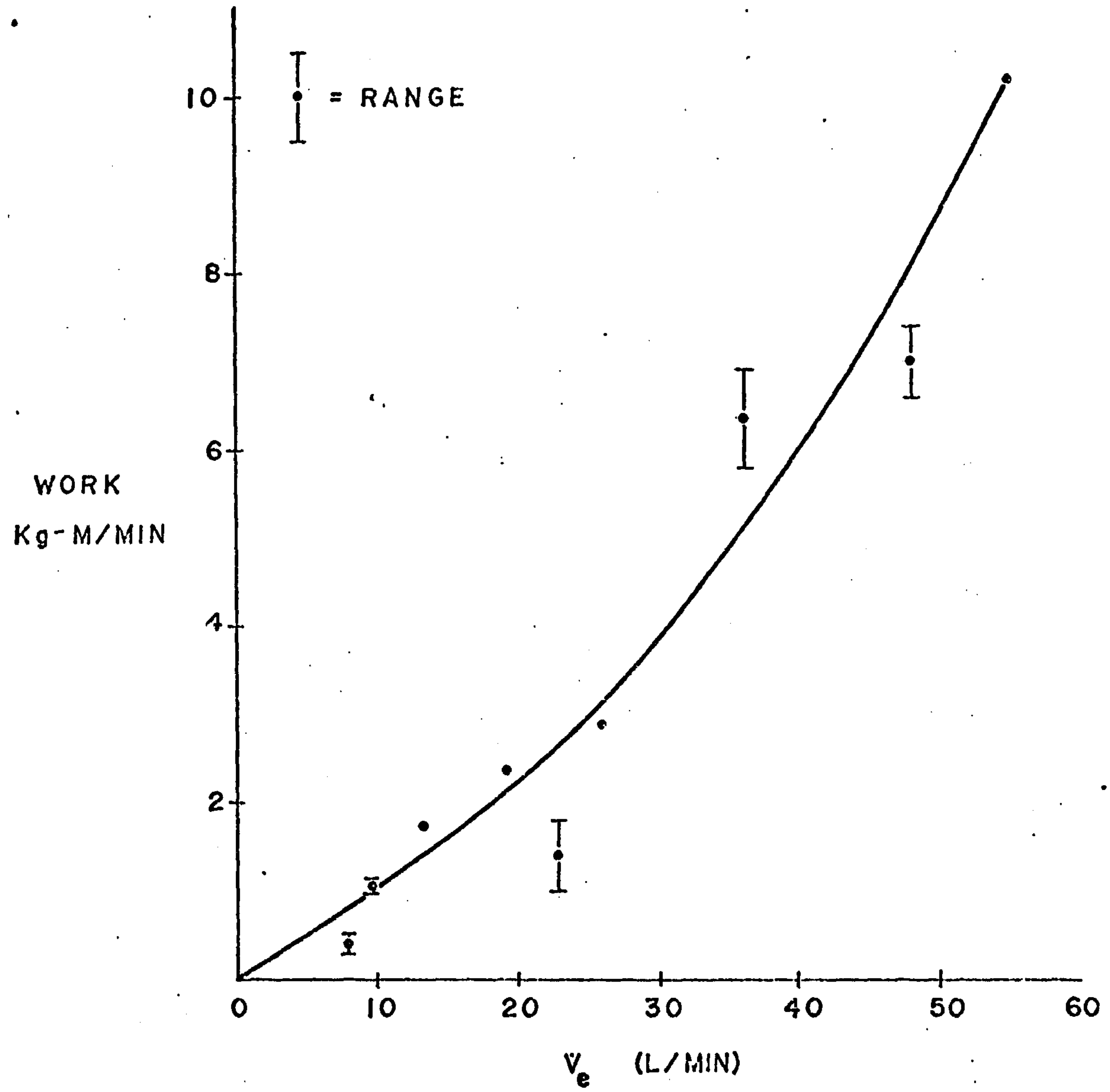

FIG. 22 - TOTAL INTRINSIC RESPIRATORY WORK AT DIFFERENT RESPIRATORY MINUTE VOLUMES OF SIX SUBJECTS BREATHING N_2-O_2 THROUGH THE LOW RESISTANCE SYSTEM

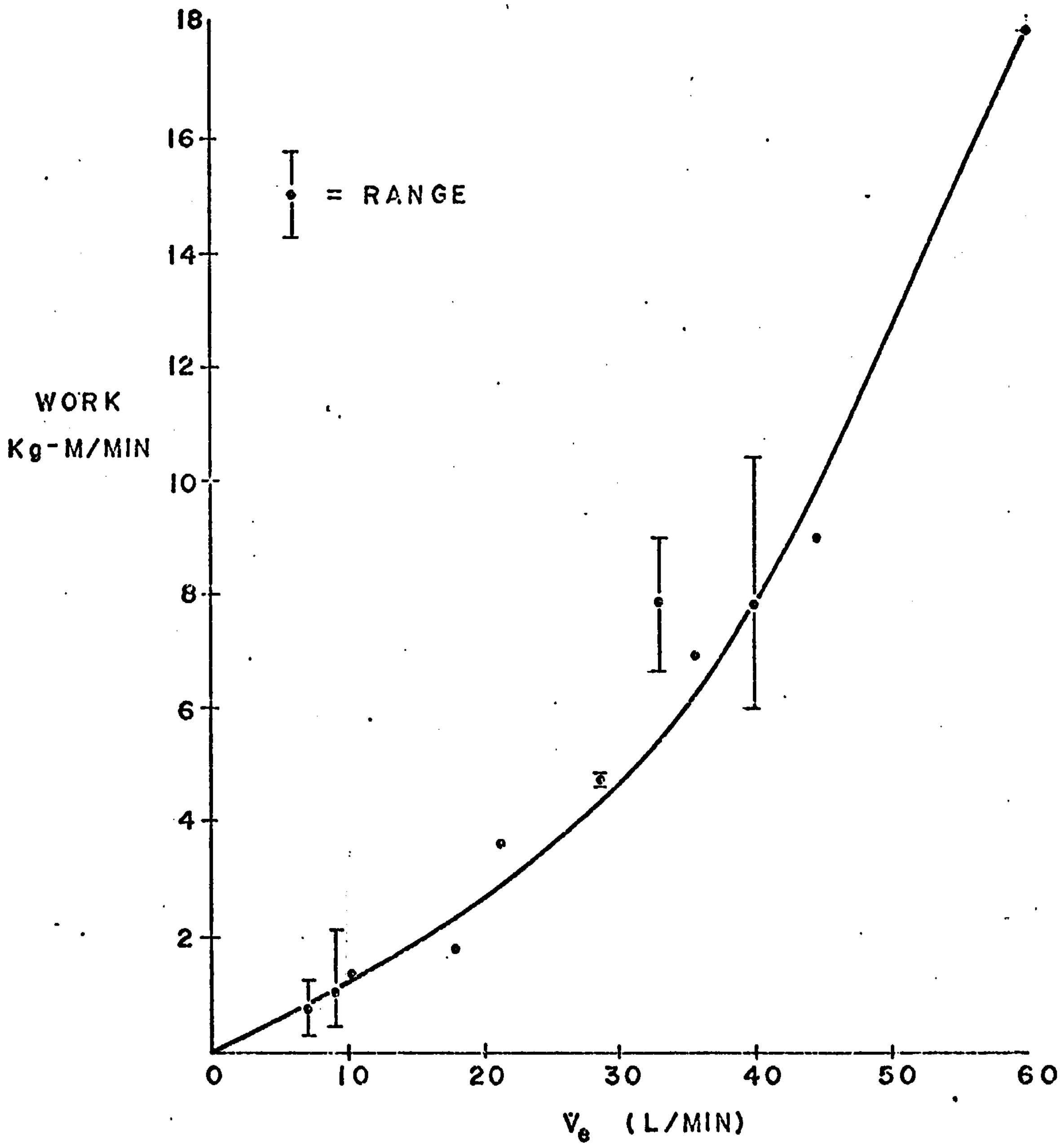

FIG. 23 - TOTAL INTRINSIC RESPIRATORY WORK AT DIFFERENT RESPIRATORY MINUTE VOLUMES OF SIX SUBJECTS BREATHING N_2-O_2 THROUGH THE MARK VIII UBA

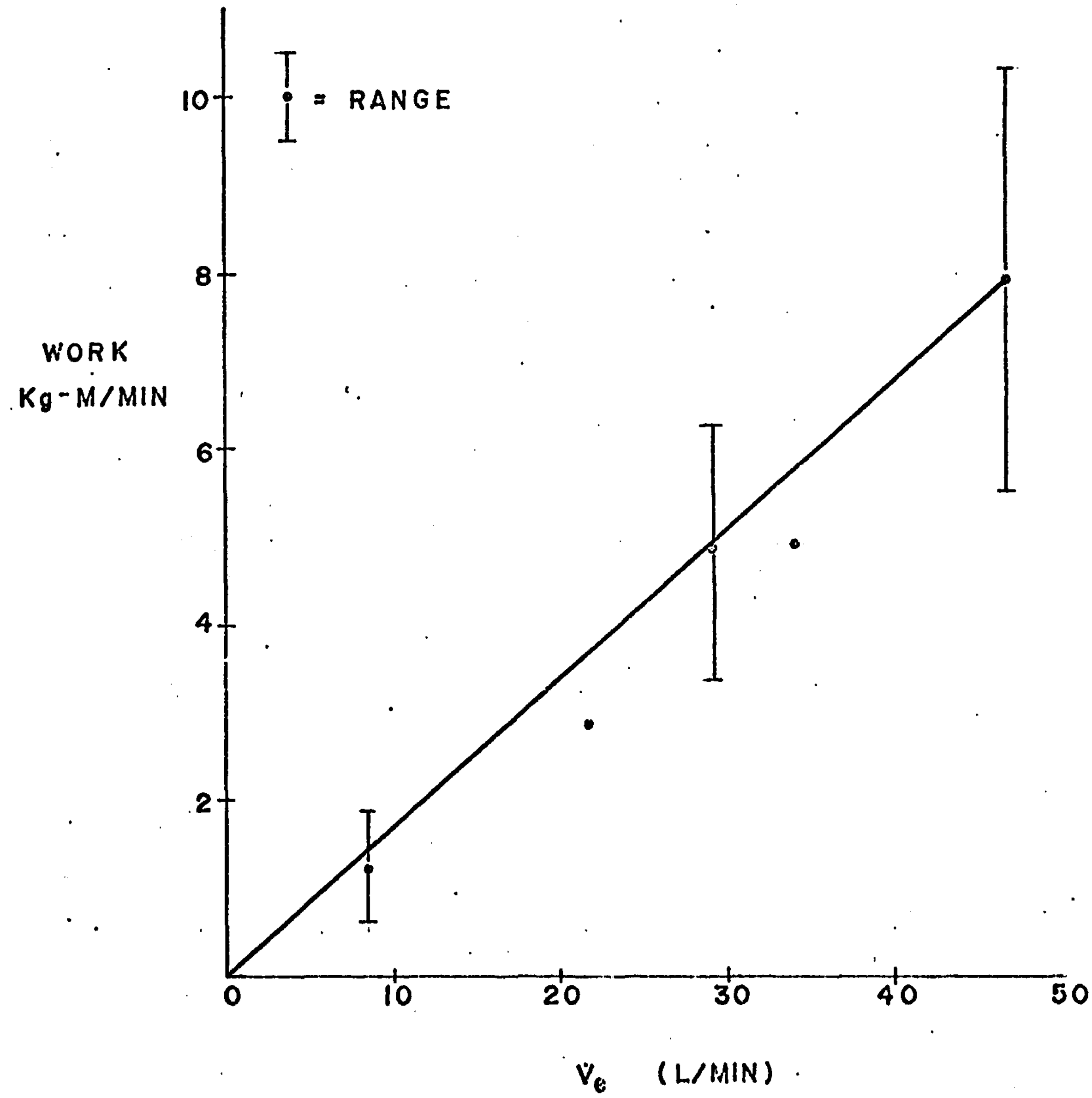

FIG. 24- TOTAL INTRINSIC RESPIRATORY WORK AT DIFFERENT RESPIRATORY MINUTE VOLUMES OF THREE SUBJECTS BREATHING N_2-O_2 THROUGH THE MARK XI UBA WITH THE KIRBY-MORGAN COMPONENT MOUTHPIECE

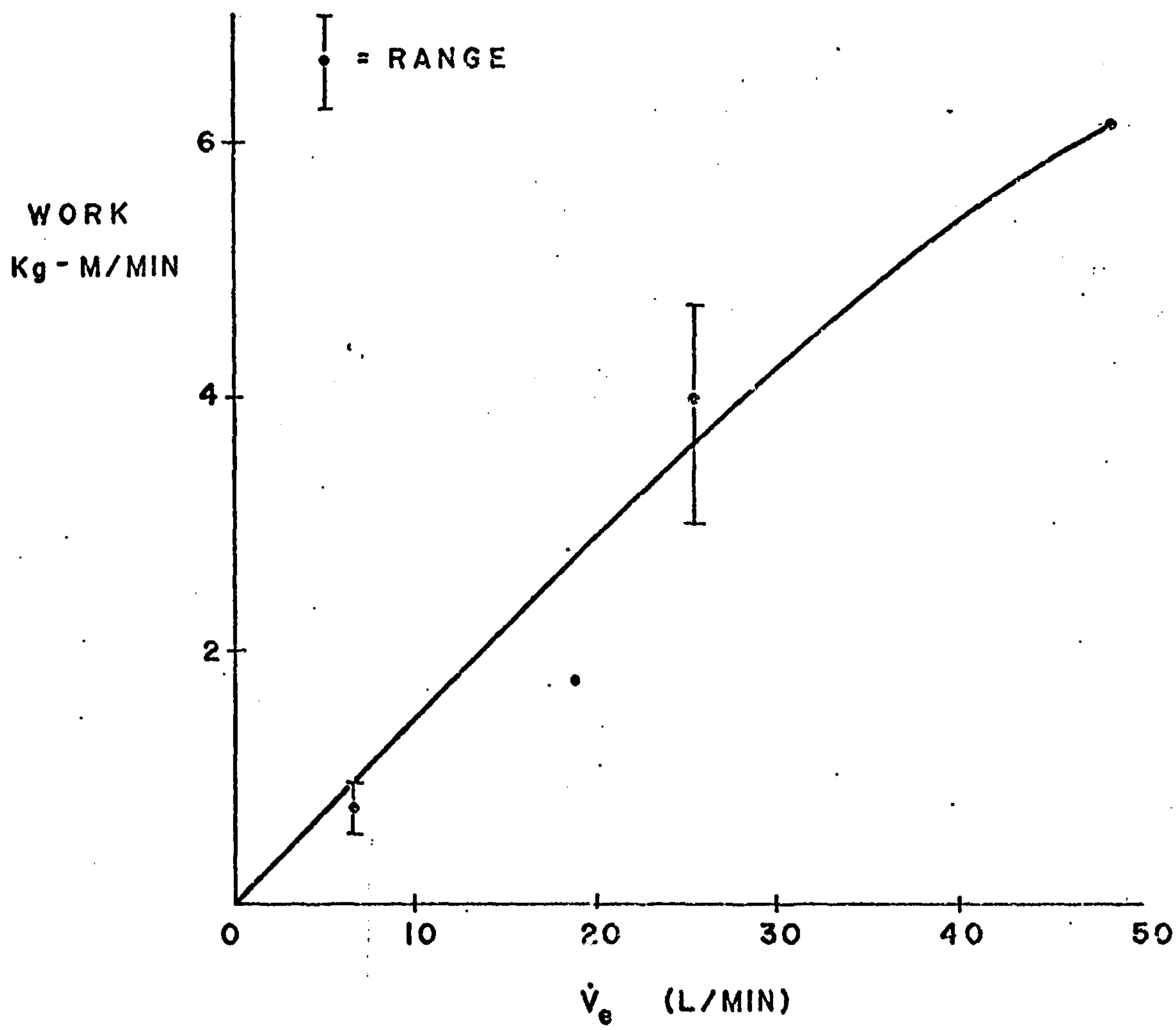

FIG. 25 - TOTAL INTRINSIC RESPIRATORY WORK AT DIFFERENT RESPIRATORY MINUTE VOLUME OF THREE SUBJECTS BREATHING N_2-O_2 THROUGH THE MARK XI WITH THE MARK VI MOUTHPIECE

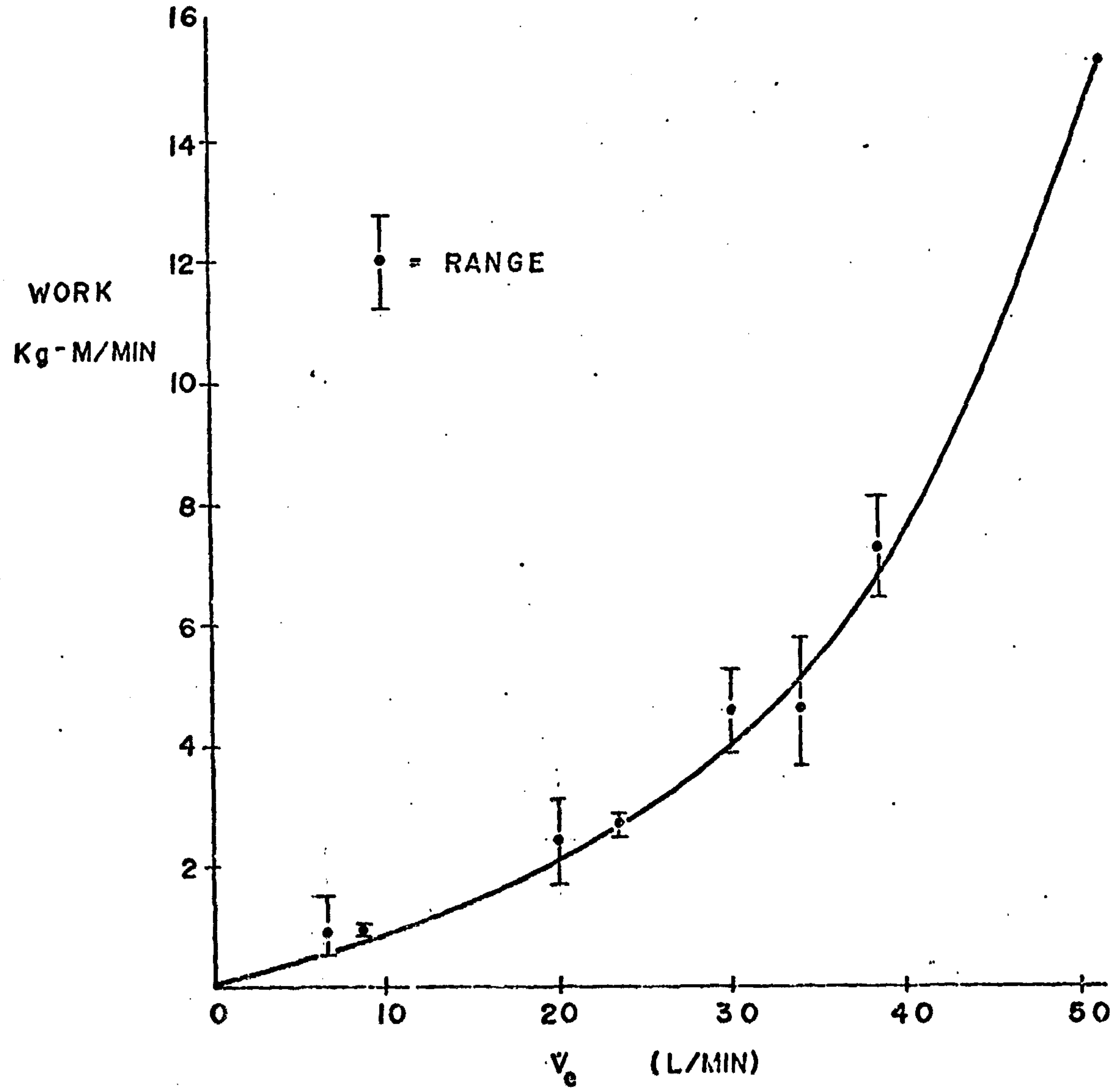

FIG. 26 - TOTAL INTRINSIC RESPIRATORY WORK AT DIFFERENT RESPIRATORY MINUTE VOLUMES OF SIX SUBJECTS BREATHING SF_6-O_2 THROUGH THE LOW RESISTANCE SYSTEM

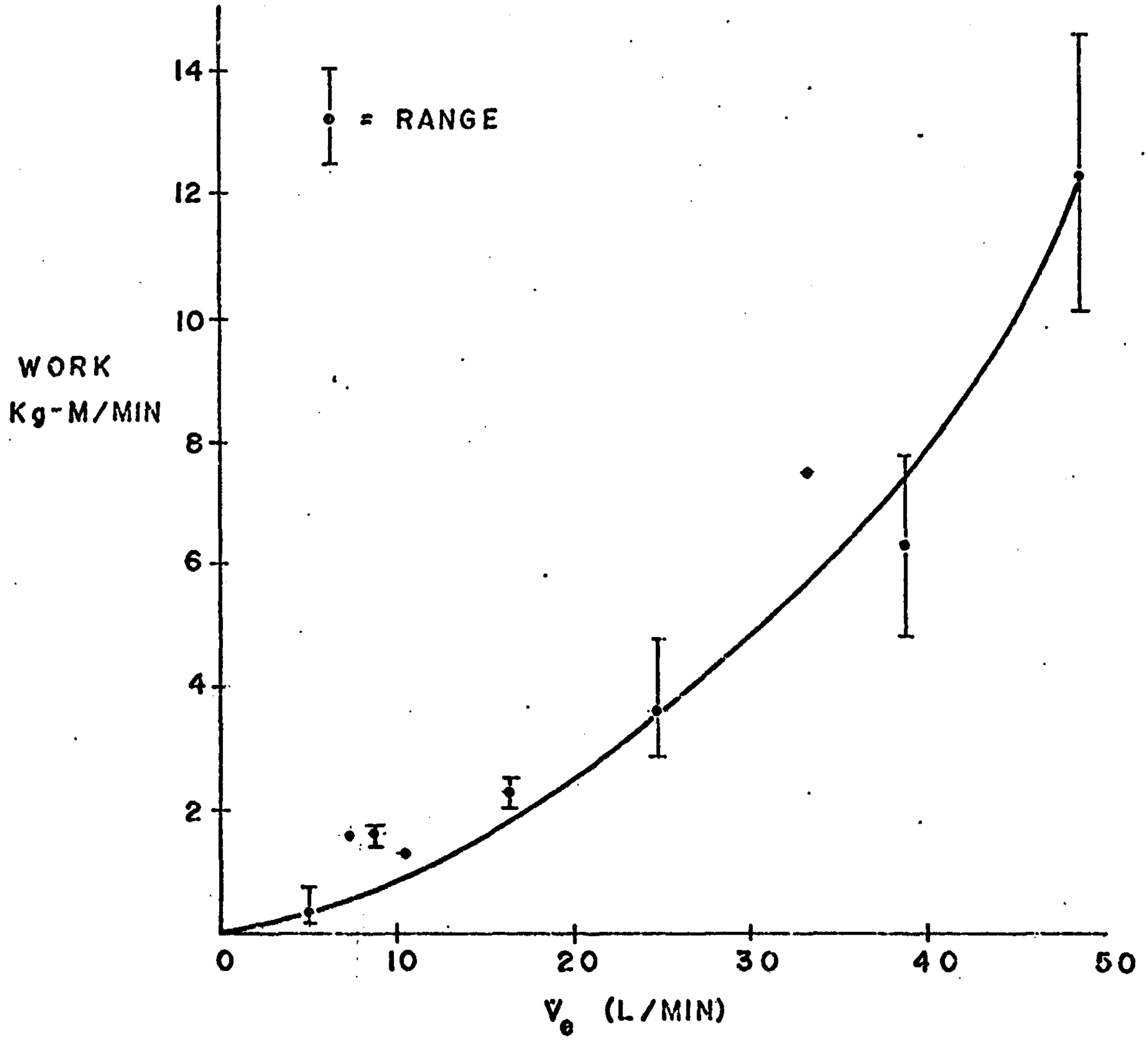

FIG. 27 - TOTAL INTRINSIC RESPIRATORY WORK AT DIFFERENT RESPIRATORY MINUTE VOLUMES OF SIX SUBJECTS BREATHING SF_6-O_2 THROUGH THE MARK VIII UBA

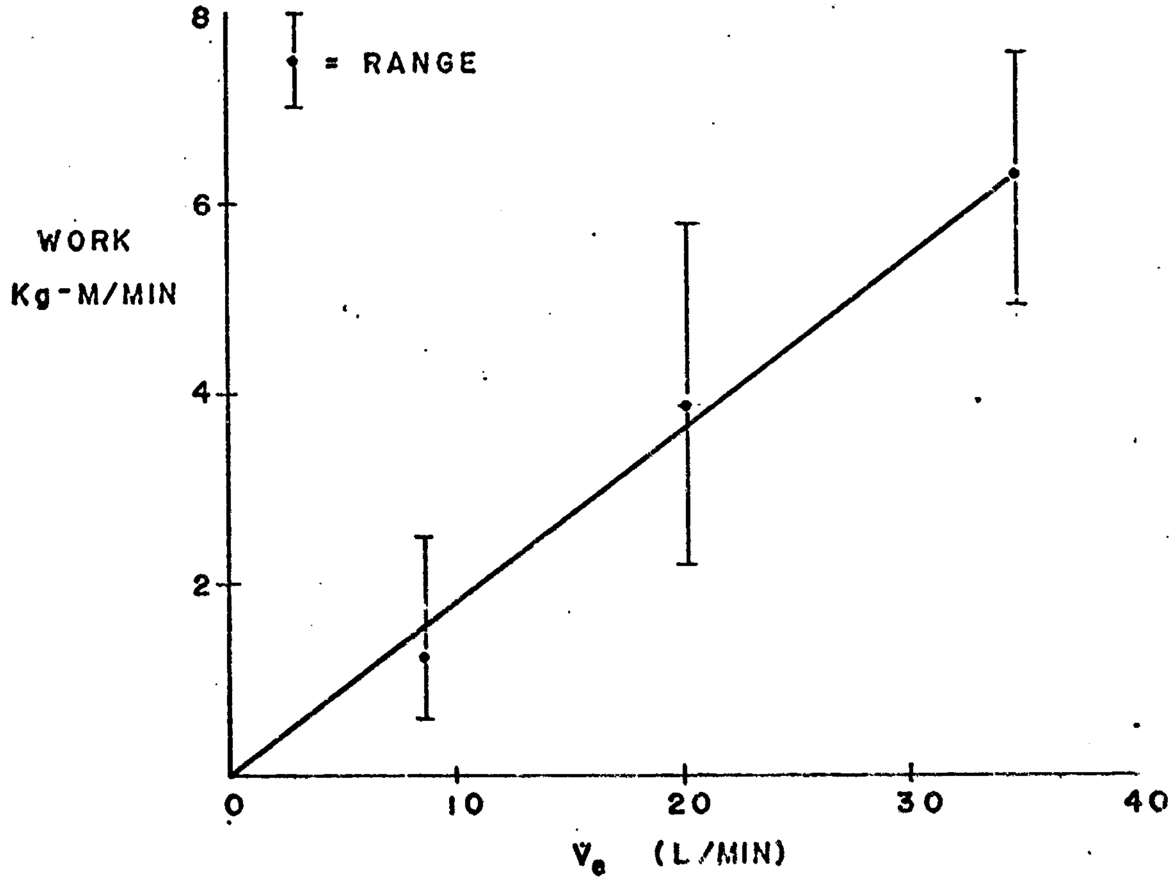

FIG. 28 - TOTAL INTRINSIC RESPIRATORY WORK AT DIFFERENT RESPIRATORY MINUTE VOLUMES OF THREE SUBJECTS BREATHING SF_6-O_2 THROUGH THE MARK XI WITH THE KIRBY-MORGAN COMPONENT MOUTHPIECE

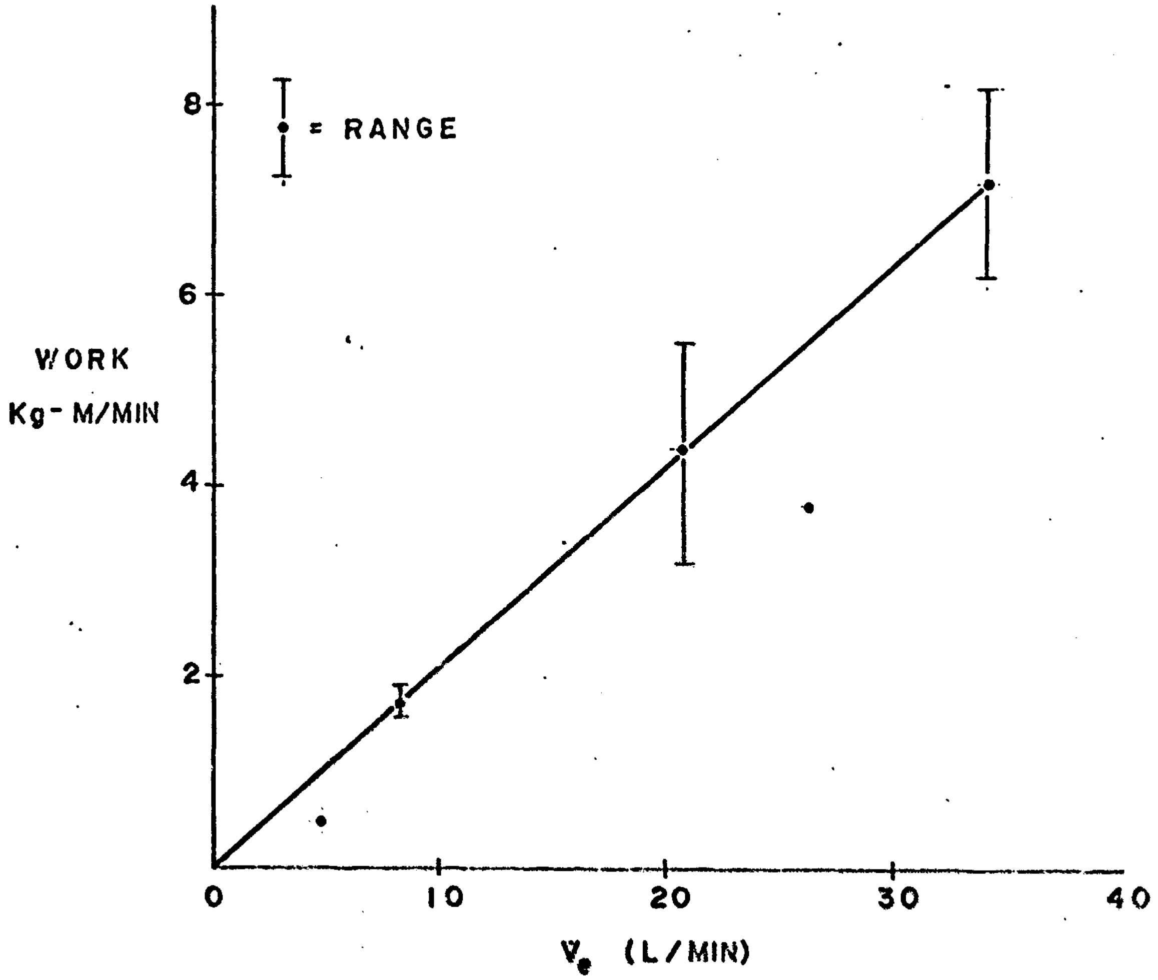

FIG. 29 - TOTAL INTRINSIC RESPIRATORY WORK AT DIFFERENT RESPIRATORY MINUTE VOLUMES OF THREE SUBJECTS BREATHING SF_6-O_2 THROUGH THE MARK XI WITH THE MARK VI MOUTHPIECE

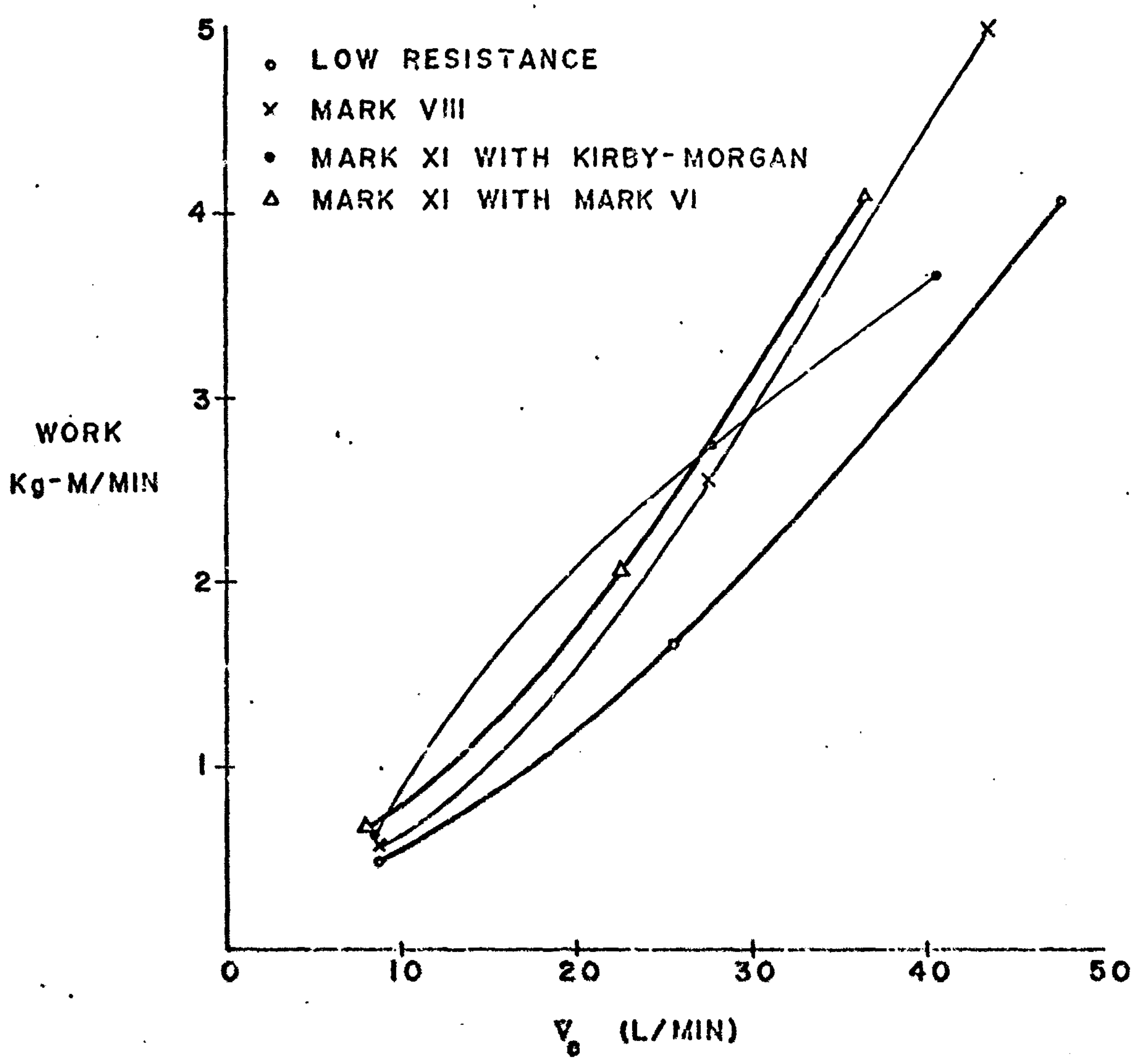

FIG. 30- INTRINSIC ELASTIC WORK BREATHING N_2-O_2 AT DIFFERENT RESPIRATORY MINUTE VOLUMES WITH THE LOW RESISTANCE SYSTEM AND THE MARK VIII AND XI UBA

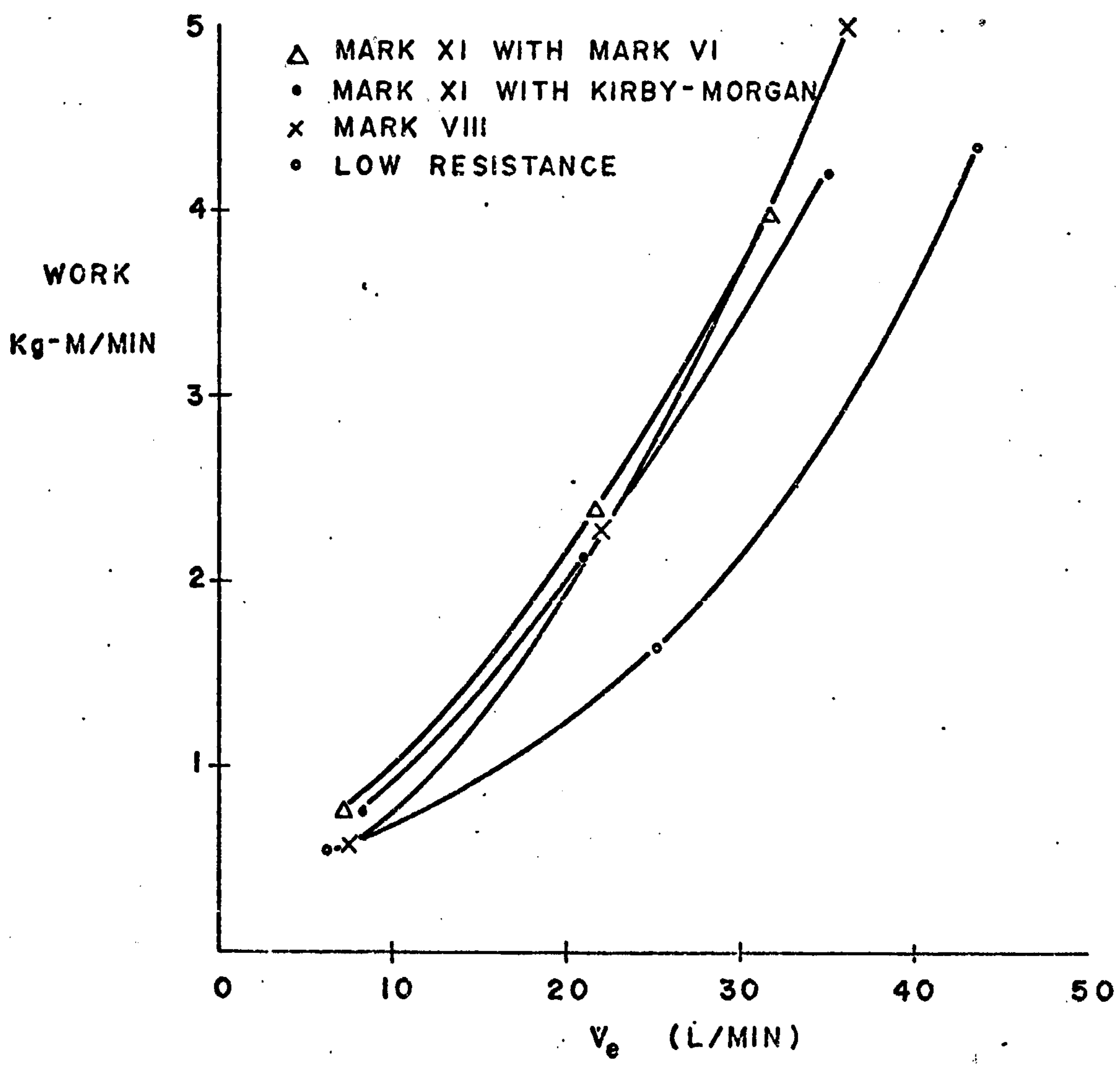

FIG. 31.- INTRINSIC ELASTIC WORK BREATHING SF_6-O_2 AT DIFFERENT RESPIRATORY MINUTE VOLUMES WITH THE LOW RESISTANCE SYSTEM AND THE MARK VIII AND XI UBA

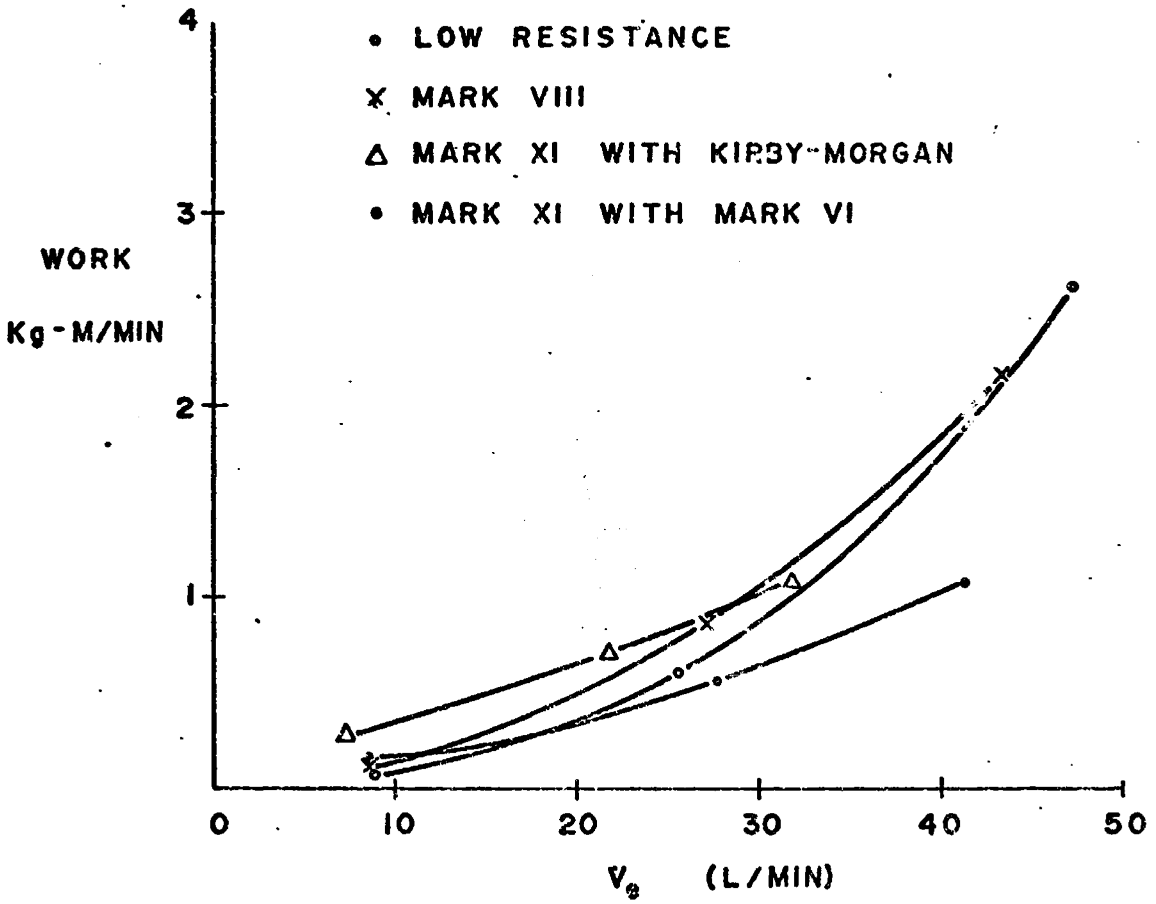

FIG. 32 - INTRINSIC FLOW RESISTIVE WORK BREATHING N_2-O_2 AT DIFFERENT RESPIRATORY MINUTE VOLUMES WITH THE LOW RESISTANCE SYSTEM AND THE MARK VIII AND XI UBA

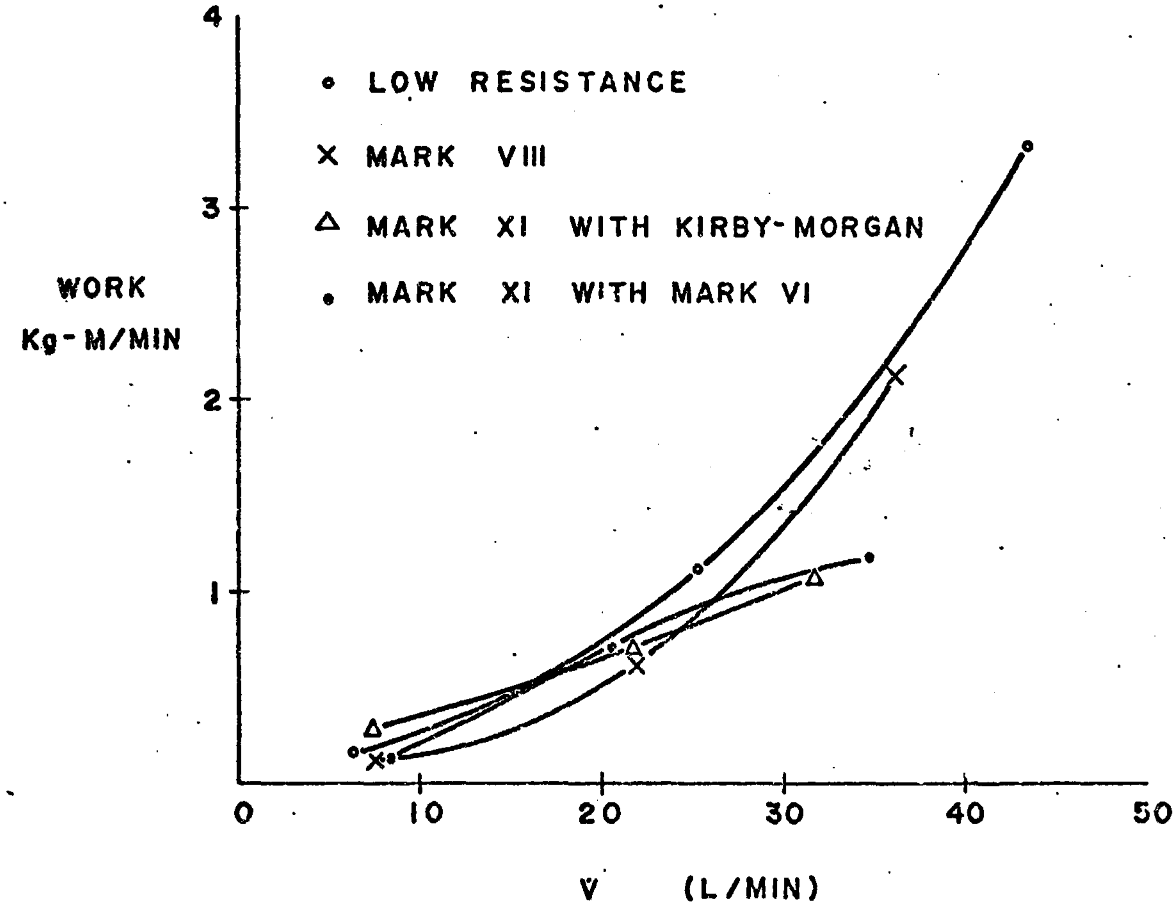

FIG. 33 - INTRINSIC FLOW RESISTIVE WORK BREATHING SF_6-O_2 AT DIFFERENT RESPIRATORY MINUTE VOLUMES WITH THE LOW RESISTANCE SYSTEM AND THE MARK VIII AND XI UBA

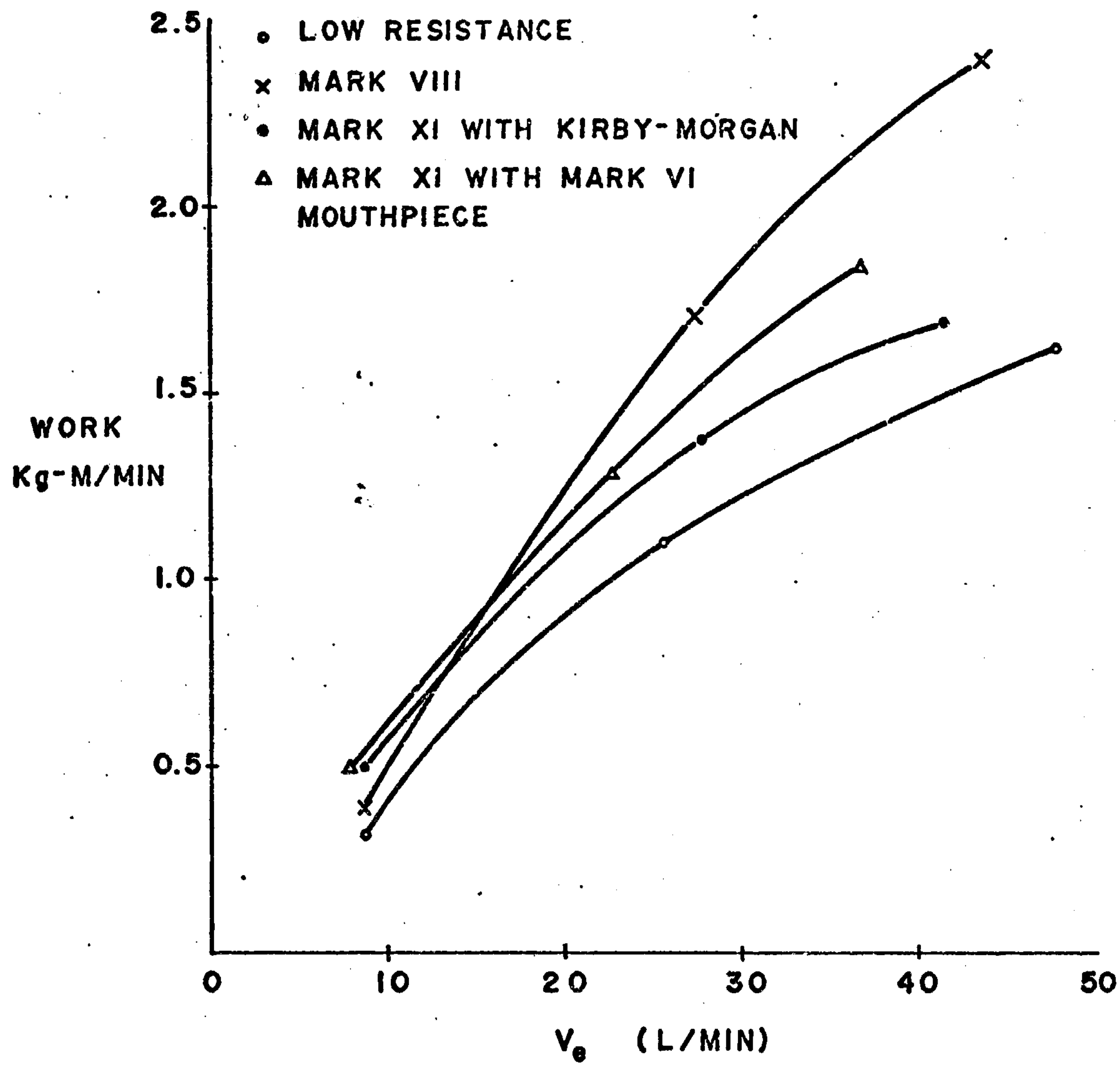

FIG. 34- INTRINSIC NEGATIVE WORK BREATHING N_2-O_2 AT DIFFERENT RESPIRATORY MINUTE VOLUMES

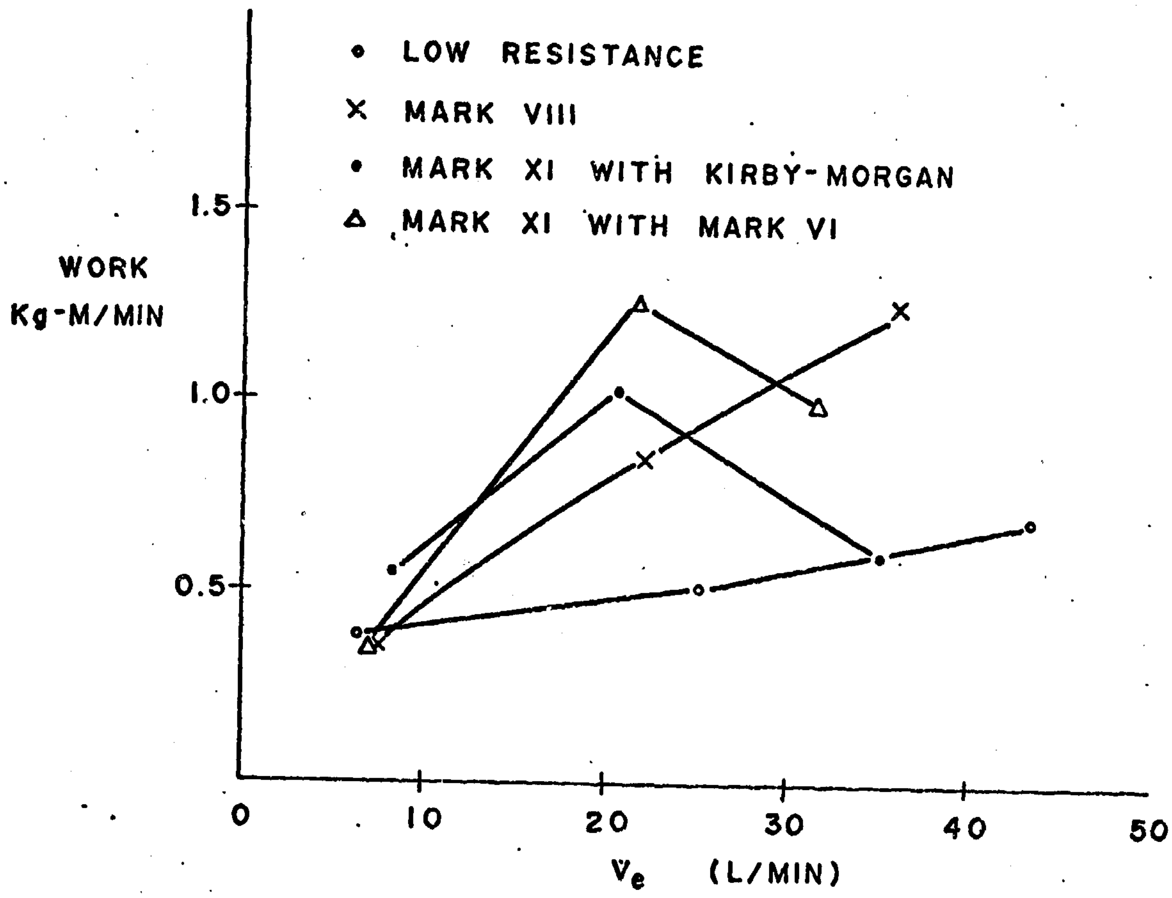

FIG. 35 - INTRINSIC NEGATIVE WORK BREATHING SF_6-O_2 AT DIFFERENT RESPIRATORY MINUTE VOLUMES WITH THE LOW RESISTANCE SYSTEM AND THE MARK VIII AND XI UBA

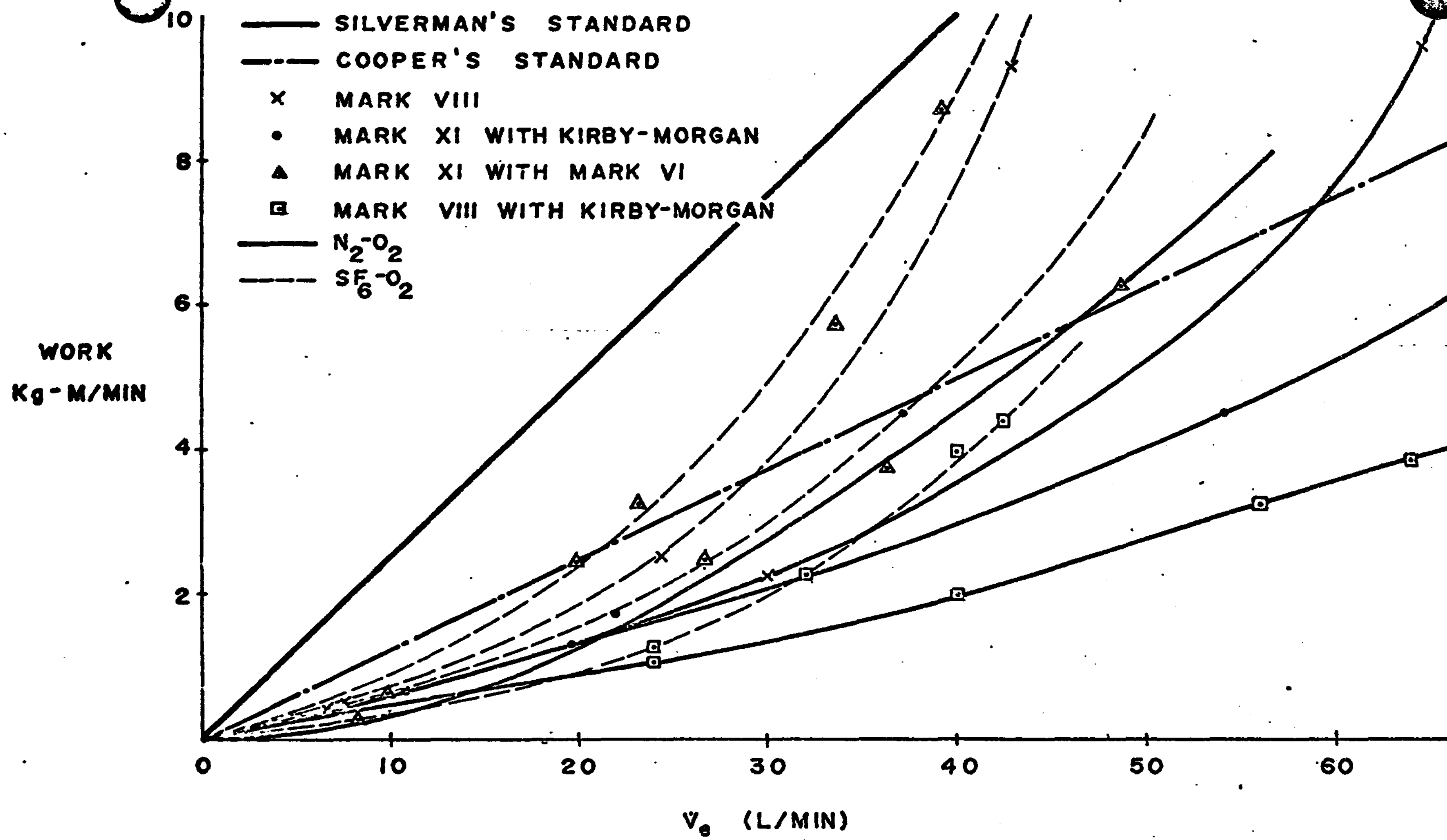

FIG. 36- TOTAL EXTRINSIC RESPIRATORY WORK AT DIFFERENT VENTILATIONS OF THE MARK VIII AND MARK XI UBA WITH N_2-O_2 AND SF_6-O_2

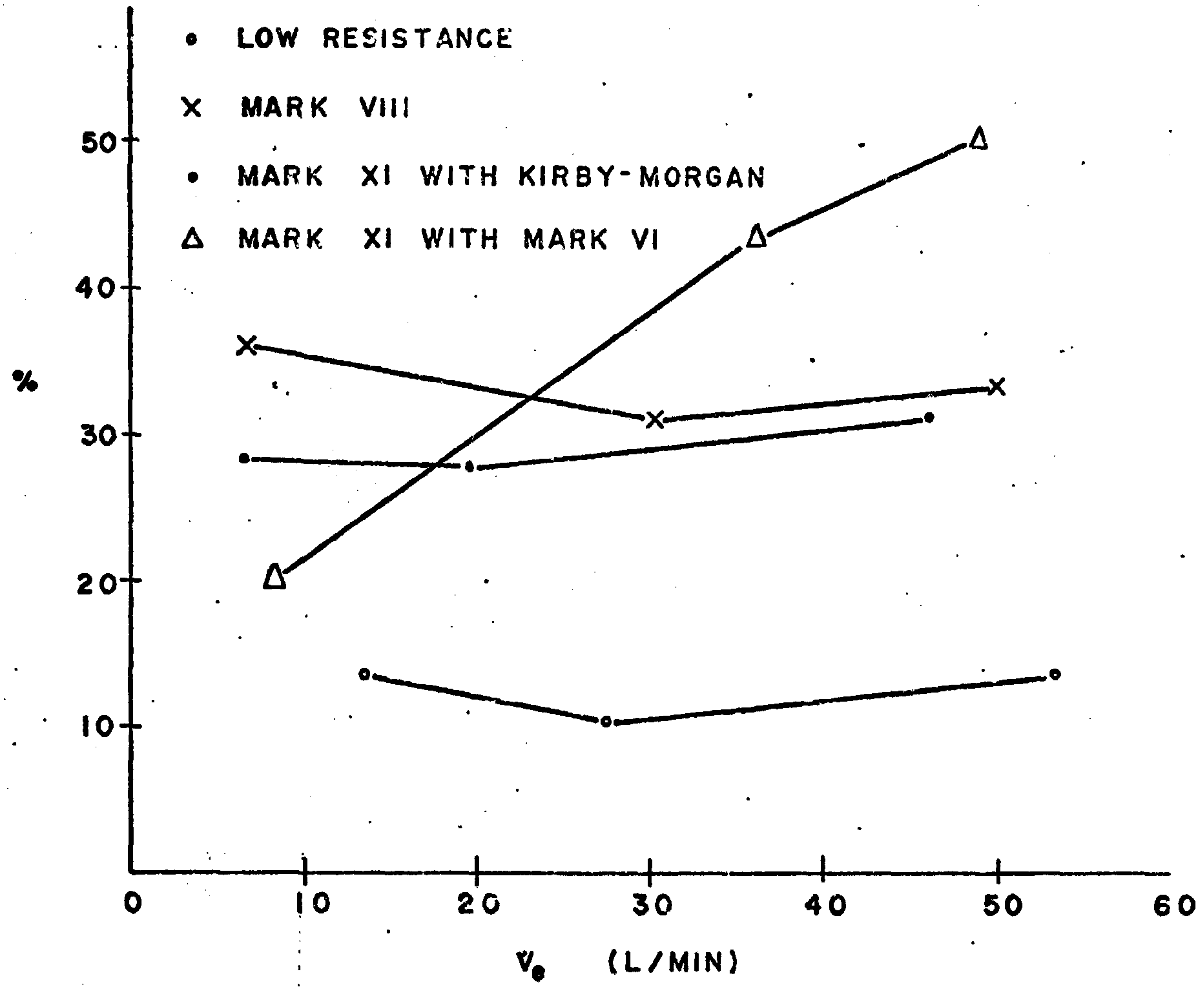

FIG. 37 - PERCENT OF TOTAL RESPIRATORY WORK DUE TO EXTRINSIC RESPIRATOR WORK BREATHING N_2-O_2 AT DIFFERENT RESPIRATORY MINUTE VOLUMES WITH THE LOW RESISTANCE SYSTEM AND THE MARK VIII AND XI UBA

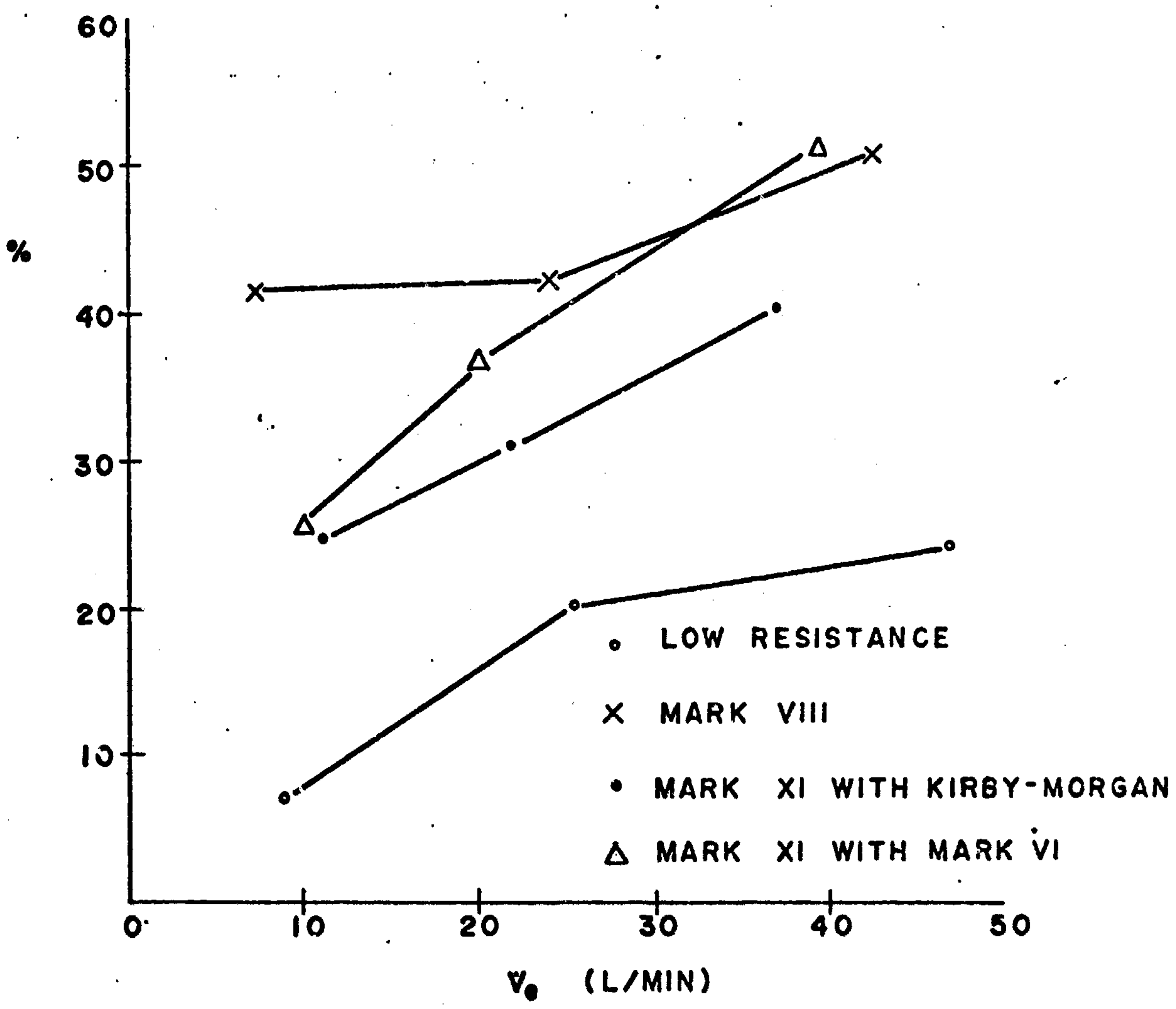

FIG. 38 - PERCENT OF TOTAL RESPIRATORY WORK DUE TO EXTRINSIC RESPIRATORY WORK BREATHING SF_6-O_2 AT DIFFERENT RESPIRATORY MINUTE VOLUMES WITH THE LOW RESISTANCE SYSTEM AND THE MARK VIII AND XI UBA

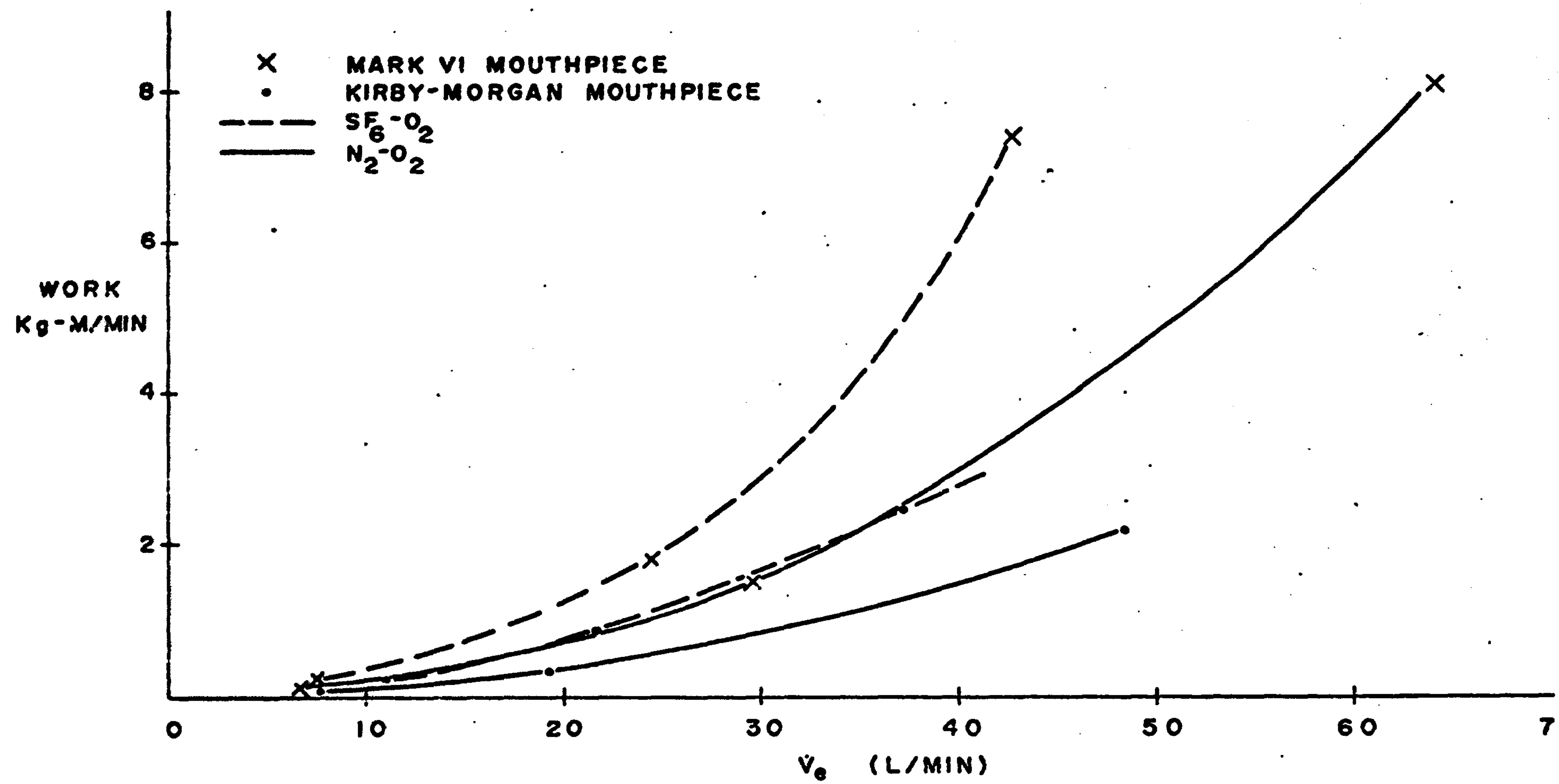

FIG. 39 - THE WORK DONE AGAINST THE KIRBY-MORGAN AND MARK VI MOUTHPIECES USING N_2-O_2 AND SF_6-O_2 GAS MIXTURES

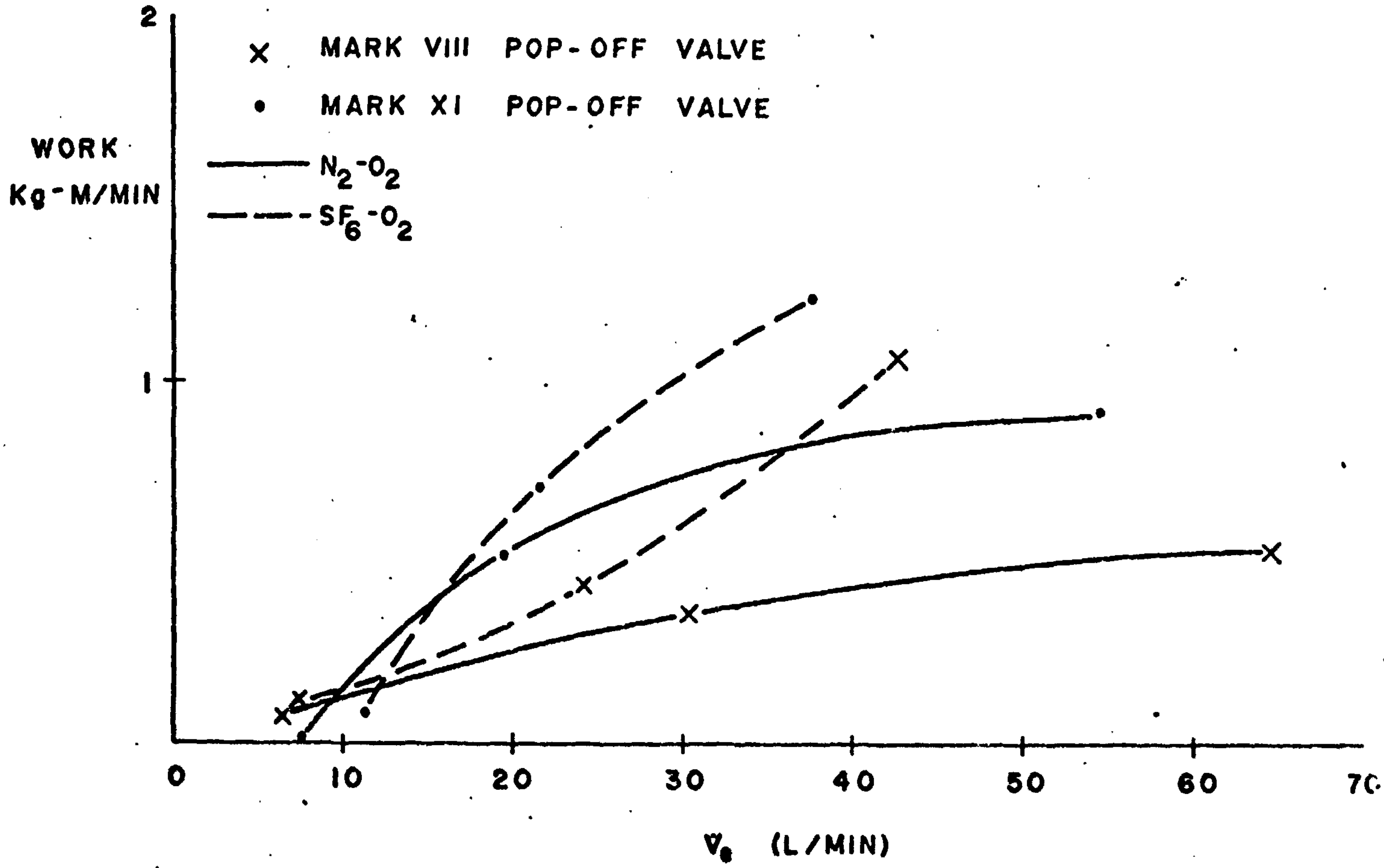

FIG. 40 - THE WORK DONE AGAINST THE MARK VIII AND XI UBA POP-OFF VALVE AT DIFFERENT VENTILATIONS USING N_2-O_2 AND SF_6-O_2 GAS MIXTURES

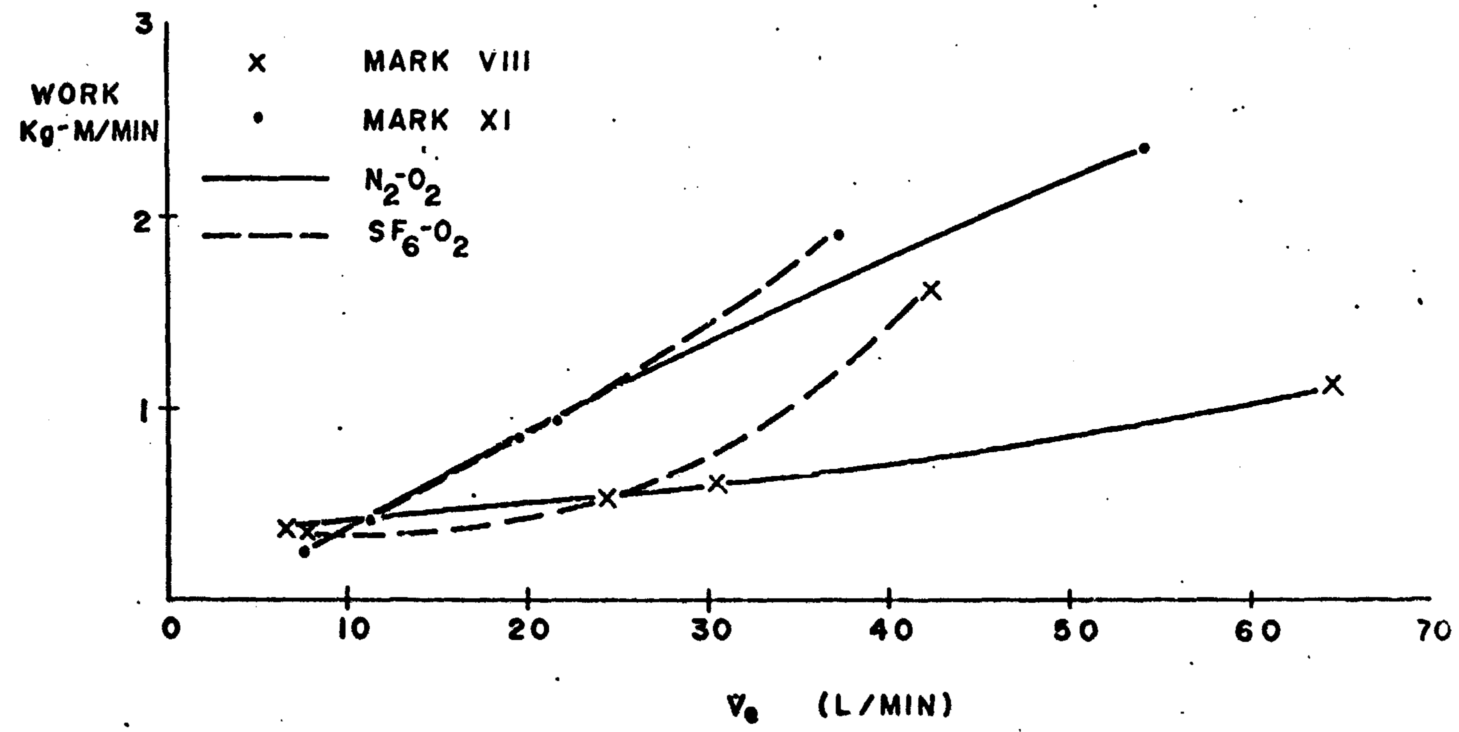

FIG. 41 - THE WORK DONE AGAINST THE MARK XI AND VIII (NOT INCLUDING WORK DUE TO MOUTHPIECE) AT DIFFERENT MINUTE VOLUMES USING N_2-O_2 AND SF_6-O_2 GAS MIXTURES

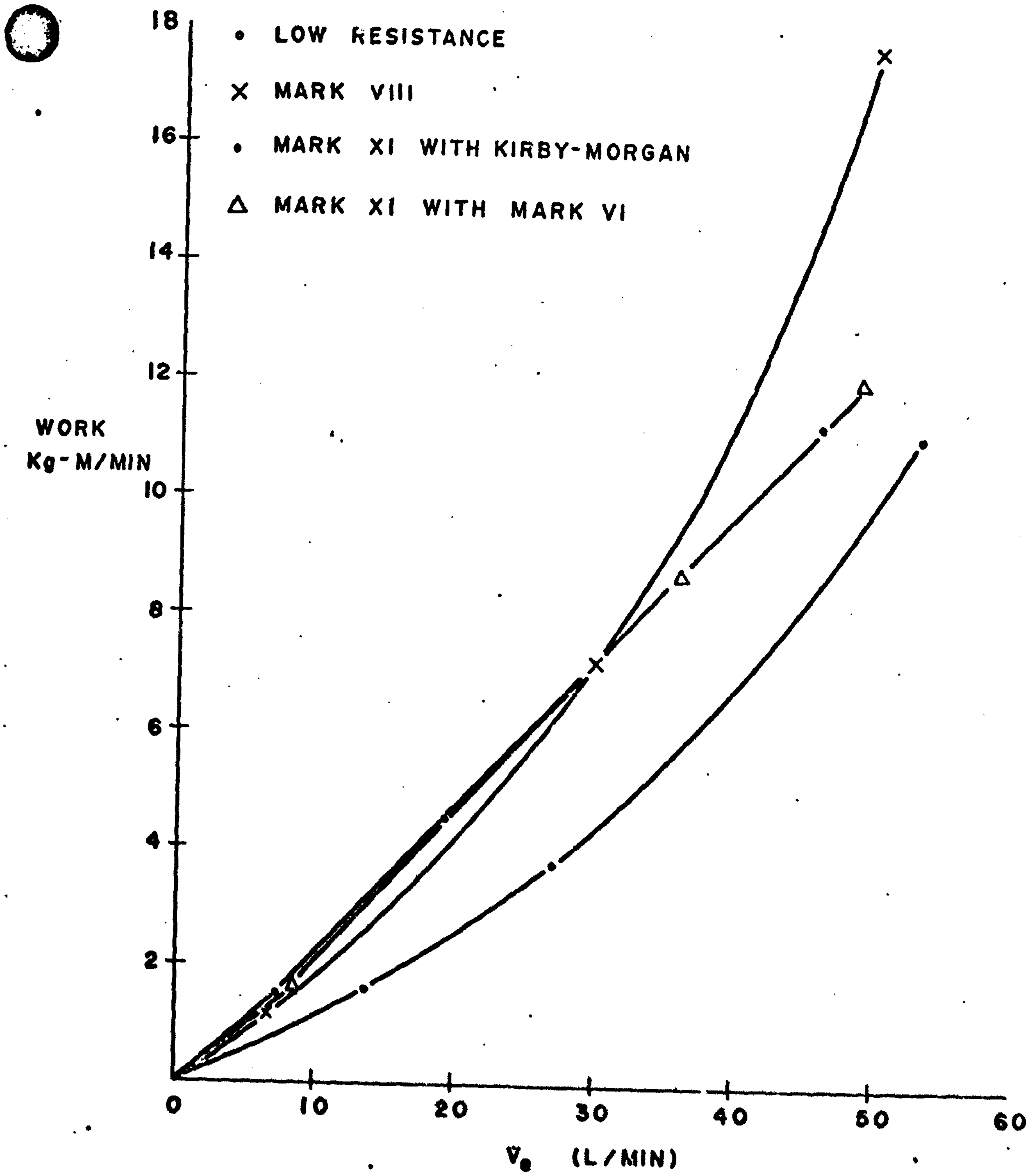

FIG. 42 - TOTAL WORK OF BREATHING N_2-O_2 WITH THE LOW RESISTANCE SYSTEM AND WITH THE MARK VIII AND XI UBA AT DIFFERENT VENTILATIONS

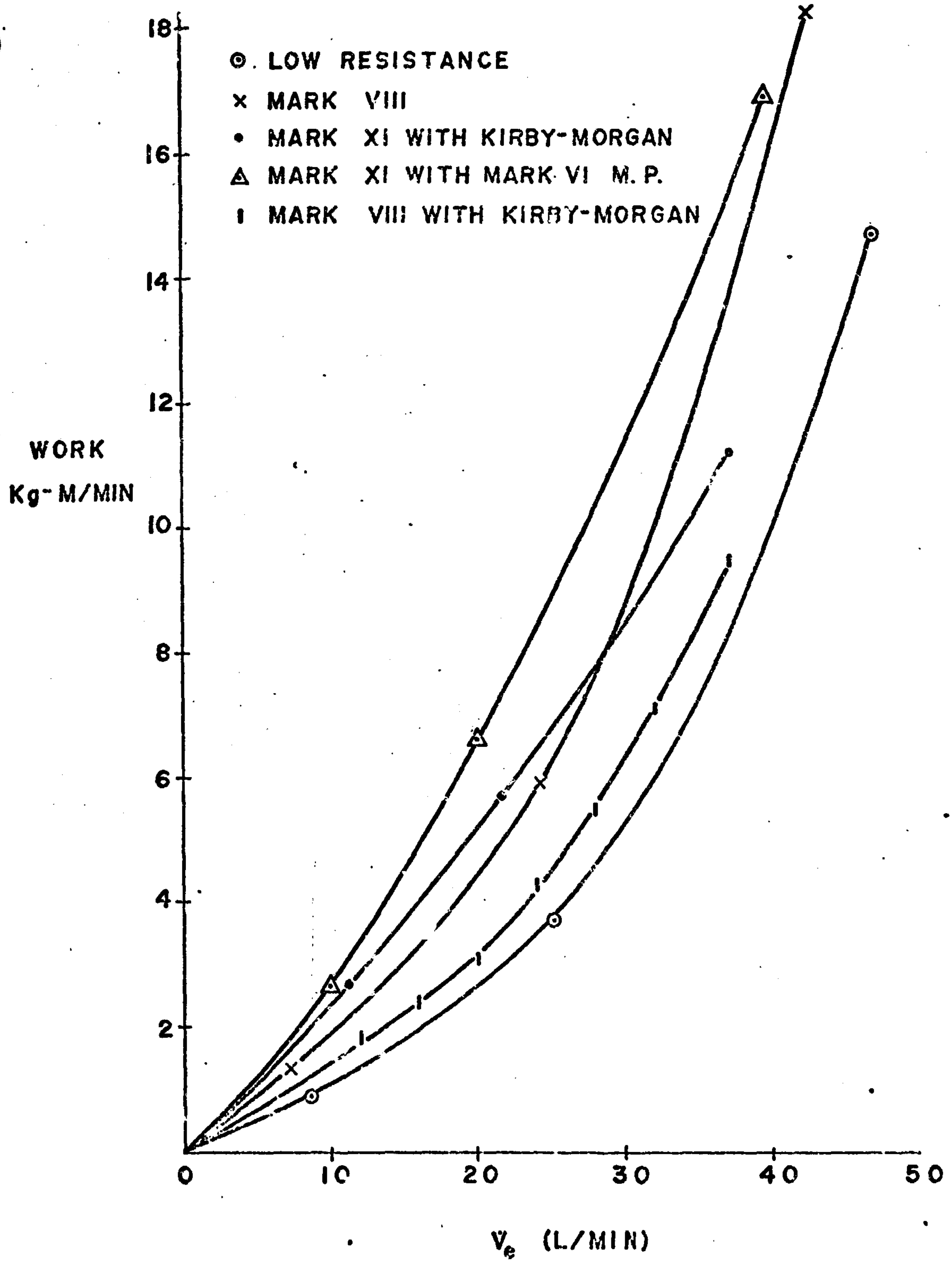

FIG. 43- TOTAL WORK OF BREATHING SF_6-O_2 WITH THE LOW RESISTANCE SYSTEM AND WITH THE MARK VIII AND XI UBA AT DIFFERENT VENTILATIONS

ACKNOWLEDGEMENTS

The authors gratefully acknowledge an indebtedness to the subjects who cheerfully endured long periods of discomfort. Lt. Rudolph Horst was unsparing in his assistance with the statistical analysis of the data. Dr. Craig Van Dyke, Dr. Robin Cook, LCDR Lloyd Flewelling, HMC Jimmy Jorren and HMC Jack Reedy fabricated necessary equipment, assisted in the conduct of the experiments, helped in the data reduction and checked calculations. EM1 Amable Mercado skillfully drew most of the figures. Dr. Nicholas Anthonisen's advice was invaluable in solving problems of data analysis. Mrs. Lorraine Muccilli and Mrs. Charlotte Bloom typed the report.

APPENDIX A

TABLES

A1 through A6

TABLE A-1

EXPERIMENTAL RESULTS FOR SUBJECT E.B.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
V_E L/Min BTPS	10.88	7.34	9.40	8.59	26.20	23.20	32.77	24.63	41.44	38.22	39.44	38.4
f Br/Min	19.8	15.8	16.8	12.4	30.0	22.3	29.3	19.7	30.0	24.7	20.3	22.7
V_t Liters BTPS	.549	.465	.560	.693	.873	1.039	1.117	1.252	1.381	1.549	1.940	1.694
TOTAL W/BREATH Kg-M	.047	.102	.124	.138	.266	.130	.229	.143	.320	.328	.512	.213
ELASTIC W/BREATH Kg-M	.023	.053	.065	.073	.014	.068	.121	.085	.174	.182	.281	.133
FLOW RESISTIVE W/BREATH Kg-M	.005	.009	.008	.005	.023	.029	.017	.024	.030	.087	.03	.032
NEGATIVE W/BREATH Kg-M	.019	.040	.051	.061	.102	.033	.091	.021	.114	.059	.202	.047

TABLE A-1 CONTINUED

EXPERIMENTAL RESULTS FOR SUBJECT E.B.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
O_2 CONSUMP. (L/Min)	.280	.282	.227	.215	.790	1.081	.942	.875	1.302	1.932	1.361	1.361
CO_2 PRODUCTION (L/Min) STPD	.180	.122	.155	.158	.693	.663	.937	.752	1.247	1.266	1.495	1.342
R	.64	.43	.68	.73	.88	.61	.99	.86	.96	.66	1.10	.99
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	33.5	42.5	33.5	30.3	37.1	37.2	36.5	37.5	35.6	38.1	41.8	39.6
MEASURED $P_{A_{CO_2}}$ (mm Hg)	38.9	38.0	38.0	36.5	37.4	38.9	39.8	40.2	37.8	40.2	44.8	44.3
PULSE RATE (BEATS/MIN)	70	70	75	76	120	112	142	133	158	156	168	160

TABLE A-1

EXPERIMENTAL RESULTS FOR SUBJECT E.B.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP
V_e L/Min BTPS	10.45	8.71	10.19	9.85	25.75	22.59	27.91	21.31	48.15	36.88	47.38	35.77
f Br/Min	17.8	15.6	17.2	18.4	19.3	18.0	22.0	16.7	29.0	20.3	29.7	17.2
V_t Liters BTPS	.587	.558	.592	.535	1.332	1.255	1.269	1.278	1.660	1.814	1.597	2.077
TOTAL W/BREATH Kg-M	.120	.114	.108	.136	.243	.304	.285	.217	.212	.405	.349	.377
ELASTIC W/BREATH Kg-M	.060	.059	.053	.07	.132	.159	.150	.120	.112	.254	.191	.237
FLOW RESISTIVE W/BREATH Kg-M	.006	.088	.008	.004	.017	.049	.030	.045	.081	.090	.039	.088
NEGATIVE W/BREATH Kg-M	.053	.046	.047	.062	.094	.096	.105	.053	.020	.061	.118	.052

TABLE A-1 CONTINUED

EXPERIMENTAL RESULTS FOR SUBJECT E.B.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP
O_2 CONSUMP. (L/Min)	.247	.244	.285	.267	.716	.838	.908	.841	1.476	1.473	1.921	1.171
CO_2 PRODUCTION (L/Min) STPD	.187	.175	.177	.157	.759	.673	.897	.790	1.460	1.351	1.389	1.248
R	.76	.72	.62	.59	1.06	.80	.99	.94	.99	.92	.72	1.07
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	34.5	41.0	33.6	34.7	36.3	36.5	39.4	44.6	34.5	40.9	33.8	38.1
MEASURED $P_{A_{CO_2}}$ (mm Hg)	39.1	36.0	39.4	38.0	43.4	39.3	44.2	44.0	39.8	43.6	44.2	46.4
PULSE RATE (BEATS/Min)	70	70	84	82	117	129	144	142	158	158	172	176

TABLE A-2

EXPERIMENTAL RESULTS FOR SUBJECT B.D.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
$\dot{V}_e$ L/Min BTPS	6.25	6.42	7.38	8.75	22.53	20.66	29.35	25.60	47.89	34.65	44.65	43.87
f Br/Min	10.4	12.6	8.3	11.4	19.0	18.7	19.0	18.3	27.0	25.7	24.3	24.3
V_t Liters BTPS	.601	.510	.886	.771	1.186	1.105	1.545	1.397	1.774	1.348	1.835	1.803
TOTAL W/BREATH Kg-M	.048	.045	.148	.125	.093	.088	.259	.266	.275	.142	.368	.415
ELASTIC W/BREATH Kg-M	.025	.022	.072	.062	.039	.031	.143	.147	.074	.028	.199	.230
FLOW RESISTIVE W/BREATH Kg-M	.007	.008	.011	.012	.033	.049	.020	.023	.176	.111	.046	.094
NEGATIVE W/BREATH Kg-M	.017	.014	.065	.051	.021	.008	.096	.097	.025	.003	.122	.092

TABLE A-2
CONTINUED.

EXPERIMENTAL RESULTS FOR SUBJECT B.D.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
O_2 CONSUMP. (L/Min)	.245	.235	.185	.199	1.062	.989	.975	1.008	2.125	1.813	1.494	1.833
CO_2 PRODUCTION (L/Min) STPD	.155	.113	.182	-.164	.784	.665	1.036	.835	1.706	1.241	1.711	1.745
R	.63	.48	.98	.82	.74	.67	1.06	.83	.80	.68	1.15	.95
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	45.8	38.9	34.9	28.7	43.1	40.9	40.8	38.9	39.7	42.6	42.6	44.5
MEASURED $P_{A_{CO_2}}$ (mm Hg)	36.9	38.1	37.7	39.7	43.6	40.9	43.1	47.7	41.5	42.4	43.1	47.7
PULSE RATE (BEATS/Min)	54	60	60	56	95	99	98	100	154	150	154	155

TABLE A-2

EXPERIMENTAL RESULTS FOR SUBJECT B.D.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP
V_e L/Min BTPS	7.96	7.91	8.21	9.69	23.69	22.49	34.09	21.06	35.93	31.56	46.37	34.21
f Br/Min	11.5	13.0	10.17	16.6	18.0	19.3	24.3	23.3	23.0	23.0	27.0	28.3
V_t Liters BTPS	.692	.608	.807	.584	1.316	1.163	1.401	.903	1.562	1.372	1.717	1.208
TOTAL W/BREATH Kg-M	.084	.121	.122	.076	.236	.234	.200	.249	.526	.270	.204	.268
ELASTIC W/BREATH Kg-M	.045	.060	.062	.038	.131	.141	.116	.126	.265	.166	.104	.176
FLOW RESISTIVE W/BREATH Kg-M	.003	.009	.006	.011	.012	.012	.023	.030	.035	.039	.060	.029
NEGATIVE W/BREATH Kg-M	.036	.052	.053	.027	.094	.081	.061	.093	.225	.065	.040	.025

TABLE A-2 CONTINUED

EXPERIMENTAL RESULTS FOR SUBJECT B.D.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP
O_2 CONSUMP. (L/Min)	.218	.205	.207	.394	.719	1.001	1.370	.977	1.319	1.573	1.619	1.292
CO_2 PRODUCTION (L/Min) STPD	.162	.156	.161	.242	.745	.729	1.144	.697	1.297	1.320	1.797	1.159
R	.74	.76	.78	.61	1.04	.73	.84	.71	.98	.84	1.11	.90
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	33.7	36.9	33.7	48.9	38.0	40.8	39.9	46.7	41.7	50.8	43.9	42.3
MEASURED $P_{A_{CO_2}}$ (mm Hg)	38.7	38.5	39.9	40.6	46.7	45.7	47.9	42.4	48.2	52.1	46.9	44.0
PULSE RATE (BEATS/Min)	71	74	70	72	104	114	129	112	163	162	172	156

TABLE A-3

EXPERIMENTAL RESULTS FOR SUBJECT R.L.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MARK VIII	MARK VIII	LOW RES	LOW RES	MARK VIII	MARK VIII	LOW RES	LOW RES	MARK VIII	MARK VIII
$\dot{V}_E$ L/Min BTPS	7.28	6.24	9.31	5.52	23.40	30.22	18.19	16.97	48.36	68.08	41.08	33.32
f Br/Min	6.8	7.0	5.9	5.0	19.7	22.7	7.7	11.3	28.7	29.3	18.8	20.0
V_T Liters BTPS	1.057	.893	1.591	1.104	1.190	1.333	2.539	1.508	1.680	2.321	2.191	1.666
TOTAL W/BREATH Kg-M	--	.222	.205	.154	.052	.170	.241	.212	.230	.355	.38	.373
ELASTIC W/BREATH Kg-M	.039	.105	.104	.080	.014	.074	.114	.100	.104	.180	.179	.177
FLOW RESISTIVE W/BREATH Kg-M	.014	.020	.003	.011	.034	.067	.022	.057	.075	.148	.083	.131
NEGATIVE W/BREATH Kg-M	--	.097	.098	.064	.004	.029	.106	.055	.051	.027	.118	.065

TABLE A-3 CONTINUED

EXPERIMENTAL RESULTS FOR SUBJECT R.L.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
O_2 CONSUMP. (L/Min)	.389	.294	.266	.162	.946	1.101	.785	.735	1.777	2.398	1.493	1.308
CO_2 PRODUCTION (L/Min) STPD	.213	.190	.262	.154	.802	.940	.754	.695	1.634	2.309	1.652	1.304
R	.55	.65	.98	.82	.83	.85	.96	.95	.92	.96	1.11	1.00
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	40.9	42.4	32.4	31.2	42.4	39.3	44.2	47.6	38.1	36.1	43.7	44.4
MEASURED $P_{A_{CO_2}}$ (mm Hg)	39.0	37.6	32.3	41.6	43.8	39.8	53.1	50.5	33.7	35.0	46.6	48.5
PULSE RATE (BEATS/Min)	67	73	76	74	132	141	120	132	180	182	180	172

TABLE A-4

EXPERIMENTAL RESULTS FOR SUBJECT W.L.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
$\dot{V}_e$ L/Min BTPS	6.49	6.21	7.12	4.46	19.48	16.34	21.75	14.74	37.53	25.64	35.78	19.26
f Br/Min	5.4	5.2	5.0	2.5	8.3	9.7	8.3	7.5	15.0	12.0	12.4	10.8
V_t Liters BTPS	1.202	1.194	1.424	1.784	2.361	2.022	2.611	1.965	2.502	2.563	2.855	1.762
TOTAL W/BREATH Kg-M	.069	.099	.050	.093	.286	.319	.442	.271	.386	.439	.545	.407
ELASTIC W/BREATH Kg-M	.047	.057	.020	.045	.175	.169	.086	.203	.275	.294	.332	.338
FLOW RESISTIVE W/BREATH Kg-M	.007	.040	.021	.035	.035	.099	.348	.049	.058	.138	.173	.060
NEGATIVE W/BREATH Kg-M	.015	.003	.009	.013	.076	.051	.009	.019	.054	.009	.040	.010

TABLE A-4 CONTINUED

EXPERIMENTAL RESULTS FOR SUBJECT W.L.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
O_2 CONSUMP. (L/Min)	.310	.388	.365	.225	1.040	1.177	1.034	1.119	1.819	2.087	1.965	1.636
CO_2 PRODUCTION (L/Min) STPD	.203	.196	.244	.158	.802	.803	.855	.683	1.498	1.603	1.684	1.151
R	.65	.51	.67	.70	.77	.68	.83	.61	.82	.77	.86	.70
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	38.9	39.0	40.7	39.7	44.1	44.6	41.6	50.8	42.3	54.8	49.3	66.9
MEASURED $P_{A_{CO_2}}$ (mm Hg)	38.9	41.5	40.7	43.0	44.1	46.1	41.6	53.0	42.3	56.5	49.3	63.0
PULSE RATE (BEATS/Min)	74	63	77	62	115	96	120	102	152	138	178	142

TABLE A-4 EXPERIMENTAL RESULTS FOR SUBJECT W.L.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP
$\dot{V}_e$ L/Min BTPS	5.88	4.70	6.96	4.87	19.08	20.26	21.46	18.95	26.04	26.65	30.12	34.39
f Br/Min	2.33	2.83	2.33	2.13	7.75	9.25	7.83	8.25	9.5	10.75	9.25	11.94
V_t Liters BTPS	2.524	1.661	2.987	2.286	2.462	2.190	2.741	2.297	2.741	2.479	3.256	2.880
TOTAL W/BREATH Kg-M	.232	.164	.244	.275	.223	.346	.364	.266	.322	.351	.367	.414
ELASTIC W/BREATH Kg-M	.122	.071	.127	.144	.143	.179	.264	.174	.225	.280	.266	.301
FLOW RESISTIVE W/BREATH Kg-M	.052	.066	.059	.089	.038	.114	.058	.087	.070	.049	.053	.103
NEGATIVE W/BREATH Kg-M	.058	.027	.058	.042	.043	.053	.042	.005	.027	.021	.048	.009

TABLE A-4 CONTINUED

EXPERIMENTAL RESULTS FOR SUBJECT W.L.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP	MK XI MK 6 MP	MK XI MK 6 MP	MK XI KM MP	MK XI KM MP
O_2 CONSUMP. (L/Min)	.362	.270	.365	.345	.872	1.200	.969	1.177	1.293	1.508	1.432	1.575
CO_2 PRODUCTION (L/Min) STPD	.217	.173	.239	.205	.816	.899	1.084	.917	1.335	1.328	1.729	1.698
R	.60	.64	.65	.59	.94	.75	1.12	.78	1.03	.88	1.21	1.08
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	38.9	41.9	35.8	45.1	45.4	47.9	54.8	52.5	53.6	52.8	59.3	51.8
MEASURED $P_{A_{CO_2}}$ (mm Hg)	40.7	40.9	45.5	44.5	50.2	46.4	48.4	51.6	53.6	5.05	61.0	52.9
PULSE RATE (BEATS/Min)	74	74	68	58	125	127	122	142	148	153	142	165

TABLE A-5

EXPERIMENTAL RESULTS FOR SUBJECT C.T.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
V_E L/Min BTPS	13.17	8.58	9.86	10.28	26.68	24.02	28.14	24.34	52.89	38.55	40.70	39.43
f Br/Min	16.6	13.2	11.4	12.6	22.2	16.7	17.3	13.3	23.7	18.7	18.3	16.3
V_t Liters BTPS	.791	.650	.865	.816	1.195	1.441	1.624	1.826	2.234	2.065	2.220	2.415
TOTAL W/BREATH Kg-M	.108	.075	.035	.102	.131	.147	.276	.222	.260	.340	.328	.481
ELASTIC W/BREATH Kg-M	.053	.037	.018	.044	.063	.076	.145	.109	.129	.190	.155	.224
FLOW RESISTIVE W/BREATH Kg-M	.008	.008	.005	.023	.019	.045	.023	.073	.053	.087	.076	.189
NEGATIVE W/BREATH Kg-M	.047	.030	.012	.035	.050	.026	.108	.040	.082	.064	.097	.068

TABLE A-5 CONTINUED

EXPERIMENTAL RESULTS FOR SUBJECT C.T.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
O_2 CONSUMP. (L/Min)	.288	.389	.214	.244	.861	1.167	.969	.947	1.733	1.965	1.512	1.573
CO_2 PRODUCTION (L/Min) STPD	.240	.179	.210	.220	.759	.723	.906	.827	1.588	1.294	1.398	1.475
R	.83	.46	.98	.90	.88	.62	.93	.87	.92	.66	.92	.94
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	27.1	35.7	30.5	31.7	35.1	35.2	36.9	37.8	32.1	36.4	37.0	39.7
MEASURED (mm Hg)	[illegible]	34.9	37.8	39.0	36.9	37.3	41.2	40.6	36.5	38.3	42.7	42.8
PULSE RATE (BEATS/MIN)	60	62	50	60	90	82	89	82	118	108	118	120

TABLE A-6 EXPERIMENTAL RESULTS FOR SUBJECT R.V.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
$\dot{V}_E$ L/Min BTPS	8.59	8.99	10.40	7.08	35.10	33.49	33.37	25.62	57.51	51.18	59.82	41.20
f Br/Min	14.4	16.8	10.8	9.8	28.3	26.0	21.3	20.0	34.0	30.0	33.3	28.8
V_t Liters BTPS	.597	.534	.963	.720	1.240	1.288	1.567	1.281	1.691	1.706	1.796	1.431
TOTAL W/BREATH Kg-M	.08	.048	.129	.164	.245	.221	.424	.389	.421	.509	.534	.506
ELASTIC W/BREATH Kg-M	.045	.022	.066	.085	.155	.123	.241	.264	.204	.277	.275	.362
FLOW RESISTIVE W/BREATH Kg-M	.004	.008	.013	.009	.030	.071	.038	.044	.173	.214	.179	.121
NEGATIVE W/BREATH Kg-M	.032	.017	.050	.070	.060	.027	.145	.081	.043	.016	.080	.059

TABLE A-6 CONTINUED.

EXPERIMENTAL RESULTS FOR SUBJECT R.V.

WORK STATE	REST	REST	REST	REST	MOD WORK	MOD WORK	MOD WORK	MOD WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK	HEAVY WORK
INSPIRED GAS	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2	N_2-O_2	SF_6-O_2
EQUIPMENT	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII	LOW RES	LOW RES	MK VIII	MK VIII
O_2 CONSUMP. (L/Min)	.302	.317	.289	.158	1.378	1.396	1.361	1.144	2.105	2.112	1.797	2.017
CO_2 PRODUCTION (L/Min) STPD	.191	.153	.228	.146	1.031	.981	1.069	.892	1.842	1.763	1.778	1.416
R	.63	.48	.79	.93	.75	.70	.79	.78	.87	.83	.99	.70
CALCULATED $P_{A_{CO_2}}$ (mm Hg)	41.1	35.8	29.7	33.1	35.8	35.3	37.0	42.3	36.1	38.9	33.1	40.2
MEASURED $P_{A_{CO_2}}$ (mm Hg)	37.3	37.4	35.0	40.5	36.8	38.0	40.4	43.1	35.2	38.9	35.4	45.0
PULSE RATE (BEATS/MIN)	64	61	67	57	125	116	116	108	162	152	168	186

APPENDIX B

At the suggestion of Cdr. Bradley, Lt. Craig Van Dyke conducted an analysis of the mathematical formulae currently used for calculating the oxygen concentration in Semi-Closed Underwater Breathing Apparatus. This analysis utilized data obtained in the UBA breathing impedance study. While not properly within the purview of this report, this analysis is considered to warrant inclusion because of its general interest to the diving community.

DETERMINATION OF OXYGEN LEVELS IN CURRENT CIRCULATING SEMI-CLOSED UNDERWATER BREATHING APPARATUS

BY

CRAIG VAN DYKE

LT, MC, USNR

1 AUGUST 1970

ABSTRACT

The primary concern in analysis of a semi-closed circuit Underwater Breathing Apparatus (UBA) is determination of the percent oxygen in the breathing medium. Dwyer in 1955 presented a method of calculating inhalation bag oxygen levels in a circulating semi-closed UBA using the injection rate, oxygen consumption, and the percent oxygen in the supply gas. However, current semi-closed UBA (Mark VI, VIII, XI) are of a different design than the model used in Dwyer's analysis. Consequently, many assumptions used in deriving Dwyer's equation are no longer valid. A more valid method of calculating inhalation bag and exhalation bag oxygen levels, and the amount of oxygen lost to the system through the exhaust valve is presented.

It was felt necessary to obtain data to determine if Dwyer's equation could still be used in determining inhalation bag oxygen levels for current semi-closed circuit UBA. A breathing impedance study of the Mark VIII and Mark XI underwater breathing apparatus was recently conducted by Submarine Development Group I. Data obtained from this study using gas mixtures of N_2-O_2 and SF_6-O_2 at three different activity levels is compared to the theoretical calculations. A close agreement between measured values and those determined by use of the equations is noted.

Because of the simplicity of Dwyer's equation and its applicability to current semi-closed circuit UBA as verified by this study, it is recommended that Dwyer's equation continue to be used in calculating inhalation bag oxygen levels of the Mark VI, VIII and XI underwater breathing apparatus. It is further recommended that all future semi-closed circuit UBA be experimentally evaluated for close agreement between measured inhalation bag oxygen levels and those calculated using Dwyer's method. The concept of 20% of each breath being lost from the system via the exhaust valve is erroneous, and should no longer be promulgated.

SUMMARY

PROBLEM:

Current semi-closed circuit underwater breathing apparatus (Mark VI, VIII, XI) are of a different design than the model used in deriving Dwyer's equation for predicting inhalation bag oxygen levels. Consequently, many of Dwyer's assumptions are no longer valid. This study was undertaken to determine if Dwyer's equation remains applicable to current semi-closed circuit underwater breathing apparatus (UBA) and to provide an alternative method of calculating inhalation bag oxygen levels. A method of calculating exhalation bag oxygen levels, and the volume of gas and oxygen lost from the system via the exhaust valve is also provided.

FINDINGS:

Dwyer's equation remains applicable to current semi-closed circuit UBA. The methods presented to calculate exhalation bag oxygen levels, and the total volume of gas and oxygen lost through the exhaust valve are also valid and accurate. Statements that 20% of each breath exhausts through the popoff valve are not correct.

RECOMMENDATIONS:

Dwyer's equation should continue to be used in calculating inhalation bag oxygen levels for the Mark VI, Mark VIII and Mark XI underwater breathing apparatus. All future semi-closed circuit UBA which are significantly different in design from that used in Dwyer's analysis should be studied to discern if Dwyer's equation is valid for predicting their inhalation bag oxygen lev...

The concept of 20% of each breath being lost through the exhaust valve is erroneous and should no longer be promulgated.

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INTRODUCTION:

The fundamental concern in the use of any semi-closed circuit underwater breathing apparatus (UBA) is to have a reliable method of calculating the inhalation bag oxygen level. It is the percentage of oxygen in the breathing medium which determines the partial pressure of oxygen to which the diver is exposed. The percentage of oxygen in the breathing medium must yield a partial pressure of oxygen which is a compromise between hypoxia (shallow depth and high oxygen consumption) and oxygen toxicity (deep depths and low oxygen consumption).

DESCRIPTION:

In 1955 Dwyer analyzed a simple recirculating semi-closed circuit UBA (Figure I), and derived an equation to determine inhalation bag oxygen levels in a static state given the injection rate, percentage of oxygen in supply gas and the diver's rate of oxygen consumption. Dwyer's mathematical analysis was based on a circulating semi-closed UBA which had a common mixing bag (i.e., common inhalation and exhalation bag.) Two postulates were necessary to derive his equation. The first assumed instantaneous mixing of the injected gas with all the gas throughout the system. Dwyer's second postulate was to assume that with instantaneous mixing the gas leaving the system through the exhaust valve had exactly the same composition as the breathing medium.

Dwyer states:

"By the second postulation, the bag oxygen level is the same as the exhaust gas oxygen level, which is subject to a very simple mathematical analysis. It is specifically the ratio of the mass of oxygen in the exhaust gas to the total mass of exhaust gas. However, the mass of oxygen in the exhaust gas is the difference between the mass of oxygen available in the injection and the mass of oxygen consumed by the diver; and the total mass of exhaust gas in the difference between the total mass of gas in the injection and mass of oxygen consumed by the diver.

Converting these statements into a mathematical formula yields the following equation:

$$B = \frac{mx - c}{m - c}$$

where:

B = bag oxygen level, percentage decimal
m = mixed-gas injection rate, standard liters per minute
x = available oxygen, standard liters per minute
c = oxygen consumption, standard liters per minute."

It is clear that current semi-closed circuit UBA, Mark VI, Mark VIII, Mark XI (Figure 2) differ from Dwyer's original model. These underwater breathing apparatus have separate inhalation and exhalation bags. Gas is injected into the hose between the Baralyme cannister and the inhalation bag. The exhaust valve is located on the exhalation bag.

Because of this change in design, neither of Dwyer's postulates are valid for current semi-closed circuit UBA. There is not instantaneous mixing of the injected gas throughout the system since the inhalation bag is physically separated from the exhalation bag. It is evident that gas composition is significantly different between the two bags. The exhalation bag has a lower oxygen percent and a much higher carbon dioxide percent than the inhalation bag. Because of this, the gas leaving the system via the exhaust valve (popoff valve) is of a different composition than that of the breathing medium.

Though not stated Dwyer's analysis makes two additional assumptions. The first is that the respiratory quotient of the diver is equal to 1, which is approximately true with exercise. His analysis also assumes an ambient pressure of 1 atmosphere absolute.

PROCEDURE:

Since Dwyer's postulates are no longer valid for current circulating semi-closed UBA, a new mathematical analysis is presented. Instantaneous mixing throughout the system is not assumed and the gas leaving the system through the exhaust valve is considered to have a different composition than gas in the inhalation bag. This analysis assumes a state of equilibrium in which the volume of gas added to the system (injection rate) is equal to the amount of gas lost from the system via the exhaust valve and the carbon dioxide, which is completely absorbed by the Baralyme. A respiratory quotient of 1 is assumed so that the volume of oxygen consumed by the diver is equal to the carbon dioxide produced by the diver. The respiratory minute volume (RMV) is considered to be the rate at which the gas is circulating through the system. The analysis assumes an ambient pressure of one atmosphere absolute.

The oxygen percent in the exhaust bag (Fe) is the ratio of the volume of oxygen entering the exhalation bag per unit of time to the total volume of gas entering the exhalation bag per unit of time. Converting these statements to a mathematical formula yields the following:

$$Fe = \frac{(B)(RMV) - c}{RMV}$$

where:

B = Inhalation bag oxygen level (decimal)
RMV = Respiratory minute volume (l/min)
c = Oxygen consumption (l/min)

Since the system is assumed to be an equilibrium and the respiratory quotient is one, the volume of gas leaving the system through the exhaust valve is the difference between the volume of gas injected into the system per unit time and the volume of gas absorbed by the Baralyme per unit of time (i.e., the oxygen consumption). Converting these statements to a mathematical formula yields the following:

$$V_e = m - c$$

where:

V_e = Volume of gas lost through the exhaust valve (l/min)

m = Injection rate (l/min)

c = Oxygen consumption (l/min).

Therefore, the amount of oxygen lost to the system through the exhaust valve per minute is:

$$V_o = (Fe)\ (m-c)$$

where:

$$V_o = \text{oxygen lost through the exhaust valve (l/min)}$$

substituting:

$$V_o = \frac{(m - c)\ [\ (RMV)\quad (B) - c]}{RMV}$$

The volume of gas lost through the exhaust valve per breath is:

$$V_f = \frac{Ve}{f} = \frac{m-c}{f}$$

where:

f = respiratory rate per minute

V_f = volume of gas lost through exhaust valve per breath

The fraction of each breath which is lost from the system through the exhaust valve is:

$$\frac{V_f}{V_t}$$

where:

V_t = tidal volume (liters)

The inhalation bag oxygen level is the ratio of the volume of oxygen entering the inhalation bag per unit time to the total volume of gas entering the inhalation bag per unit time. The volume of oxygen entering the inhalation bag is the sum of that being injected and the oxygen that is being recirculated. The volume of oxygen being recirculated is the volume of oxygen coming from the inhalation bag minus the oxygen lost from the system through the exhaust valve and by oxygen consumption. The total volume of gas entering the inhalation bag per unit time is the respiratory minute volume.

Converting these statements into mathematical formula yields the following:

$$B = \frac{mx + (B)(RMV) - c - V_o}{RMV}$$

Rearranging:

$$B = \frac{mx}{RMV} + B - \frac{c}{RMV} - \frac{V_o}{RMV}$$

$$\frac{mx}{RMV} - \frac{c}{RMV} - \frac{V_o}{RMV} = 0$$

Substituting for V_o:

$$\frac{mx}{RMV} - \frac{c}{RMV} - \frac{\dfrac{(m-c)\ [(B)\ (RMV) - c]}{RMV}}{RMV} = 0$$

$$\frac{mx}{RMV} - \frac{c}{RMV} - \frac{(m)\ (B)\ (RMV) - (B)\ (c)\ (RMV) - cm + c^2}{(RMV)^2} = 0$$

$$\frac{mx}{RMV} - \frac{c}{RMV} - \frac{(B)\ (m)}{RMV} + \frac{(B)\ (c)}{RMV} + \frac{(c)\ (m)}{(RMV)^2} - \frac{c^2}{(RMV)^2} = 0$$

$$\frac{mx}{RMV} - \frac{c}{RMV} + \frac{(c)\ (m)}{(RMV)^2} - \frac{c^2}{(RMV)^2} = \frac{(B)\ (m)}{(RMV)} - \frac{(B)\ (c)}{RMV}$$

$$\frac{mx}{RMV} - \frac{c}{RMV} + \frac{(c)\ (m)}{(RMV)^2} - \frac{c^2}{(RMV)^2} = \frac{B\ (m-c)}{(RMV)}$$

$$mx - c + \frac{cm}{RMV} - \frac{c^2}{RMV} = (B)\ (m-c)$$

$$B = \left(\frac{1}{m-c}\right) \left[mx - c + \frac{(c)\ (m)}{RMV} - \frac{c^2}{RMV}\right]$$

RESULTS AND DISCUSSION:

To determine if Dwyer's equation and the equations derived above are valid for use with current semi-closed circuit UBA, data from a breathing impedance study of the Mark VIII and Mark XI underwater breathing apparatus was used. This study occurred in a dry laboratory. Both diver and non-diver subjects were required to pedal a bicycle ergometer at different activity levels (500 and 1000 kg. m/min.) while breathing on the above underwater breathing apparatus. Subjects breathed N_2 - O_2 and SF_6 - O_2 (to simulate breathing a more dense gas at depth) gas mixtures. Numerous measurements of pressure and flows were determined including: inhalation and exhalation bag gas compositions, injection rate, oxygen percent in gas supply, subject's oxygen consumption and respiratory minute volume. Representative data from this study are compared to results obtained from the above equations in Tables 1 - 4.

Current semi-closed circuit UBA have been used for many years without any experimental evidence that Dwyer's equation is a valid method of calculating their inhalation bag oxygen levels. Table 1 compares measured inhalation bag oxygen levels with those calculated using Dwyer's equation. The calculated results compare very closely with the measured results of both the Mark VIII and Mark XI underwater breathing apparatus under all conditions of the study. Table 2 compares measured inhalation bag oxygen levels with those obtained using the equation derived above. The calculated results generally are 1 - 5% higher than both the measured values and those obtained using Dwyer's equation. No explanation for the discrepancy between measured values and those obtained using the new equation can be given at this time.

Table 3 compares the measured exhalation bag oxygen levels with those obtained using the equation derived above. The calculated results compare very closely with the measured results of both the Mark VIII and Mark XI underwater breathing apparatus under all conditions.

Table 4 presents the total volume of gas and the volume of oxygen which is lost from the system through the exhaust valve per minute. The volume of gas that passes through the exhaust valve is approximately the same at each work level. It ranges from a low of 1 liter per minute at rest to a high of 13.96 liters per minute at heavy work (1000 kg m/min.). The volume of gas which is lost through the exhaust valve per breath ranges from 0.07 liters to 1.29 liters. The fraction of each breath (tidal volume) which is lost through the popoff valve is also presented and ranges from 12% to 73%. Generally, for activity levels other than rest, the fraction of each breath which is exhausted through the popoff valve is greater than 20%. Consequently, statements that approximately 20% of each breath is lost through the exhaust valve are not correct.

CONCLUSION:

Though many of Dwyer's assumptions are not valid for current semi-closed circuit UBA, his equation for determining inhalation bag oxygen level remains applicable and should continue to be used. The mathematical equations derived above for exhalation bag oxygen levels, and the volume of gas and oxygen which exhausts through the popoff valve are valid and should be used in future calculations. Statements that 20% of each breath is exhausted through the popoff valve are incorrect and should no longer be promulgated.

All future semi-closed circuit UBA should be experimentally evaluated for close agreement between measured inhalation bag oxygen levels and those calculated using Dwyer's equation.

TABLE I

Comparison of measured and calculated inhalation bag oxygen levels using Dwyer's equation.

MARK VIII

Subject: R. L. (Non-Diver)
Gas Supply: N_2 - O_2 with 43% O_2

Work Level	O_2 Consumption (1/min)	Injection Rate (1/min)	Fi (Measured)	Fi (Calculated)
Rest	0.266	1.8	33%	33%
Moderate	0.785	9.15	37%	37%
Heavy	1.493	13.15	33%	35%
Gas Supply: SF_6 - O_2 with 38% O_2				
Rest	0.162	1.35	25%	29%
Moderate	0.735	8.5	30%	32%
Heavy	1.308	14.3	29%	31%
Subject: W. L. (Diver) Gas Supply: N_2 - O_2 with 43% O_2				
Rest	0.365	1.36	27%	22%
Moderate	1.034	9.5	35%	35%
Heavy	1.965	14.9	35%	34%
Gas Supply: SF_6 - O_2 with 38% O_2				
Rest	0.225	2.0	30%	30%
Moderate	1.119	8.65	31%	28%
Heavy	1.636	15.6	34%	30%

TABLE I

MARK XI

Subject: E. B. (Diver)
Gas Supply: $N_2 - O_2$ with 43% O_2

Work Level	O_2 Consumption (l/min)	Injection Rate (l/min)	Fi (Measured)	Fi (Calculated)
Rest	0.247	1.5	32%	31%
Moderate	0.716	6.65	32%	36%
Heavy	1.476	10.5	30%	33%
Gas Supply: $SF_6 - O_2$ with 38% O_2				
Rest	0.267	1.65	28%	26%
Moderate	0.841	8.2	29%	31%
Heavy	1.171	14.45	30%	32%
Subject: B.D. (Non-Diver) Gas Supply: $N_2 - O_2$ with 43% O_2				
Rest	0.218	1.62	34%	34%
Moderate	0.719	8.5	36%	37%
Heavy	1.319	12.35	33%	36%
Gas Supply: $SF_6 - O_2$ with 38% O_2				
Rest	--	--	--	--
Moderate	0.977	8.6	31%	30%
Heavy	1.292	14.0	31%	31%

TABLE 2

Comparison of measured and calculated inhalation bag oxygen levels using equation derived above.

MARK VIII

Subject: R. L. (Non-Diver)
Gas Supply: $N_2 - O_2$ with 43% O_2

Work Level	O_2 Consumption (l/min)	Injection Rate (l/min)	RMV	Fi (Measured)	Fi (Calculated)
Rest	0.266	1.8	9.31	33%	36%
Moderate	0.785	9.15	18.19	37%	41%
Heavy	1.493	13.15	41.08	33%	39%
Gas Supply: $SF_6 - O_2$ with 38% O_2					
Rest	0.162	1.35	5.52	25%	32%
Moderate	0.735	8.5	16.97	30%	36%
Heavy	1.308	14.3	33.22	29%	35%
Subject: W. L. (Diver) Gas Supply: $N_2 - O_2$ with 43% O_2					
Rest	0.365	1.36	7.12	27%	27%
Moderate	1.034	9.5	21.75	35%	40%
Heavy	1.965	14.9	35.78	35%	39%
Gas Supply: $SF_6 - O_2$ with 38% O_2					
Rest	0.225	2.0	4.46	30%	35%
Moderate	1.119	8.65	14.74	31%	36%
Heavy	1.636	15.6	19.26	34%	39%

TABLE 2

MARK XI

Subject: E. B. (Diver)
Gas Supply: $N_2 - O_2$ with 43% O_2

Work Level	O_2 Consumption (l/min)	Injection Rate (l/Min)	RMV	Fi (Measured)	Fi (Calculated)
Rest	0.247	1.5	10.45	32%	34%
Moderate	0.716	6.65	25.75	32%	38%
Heavy	1.476	10.5	48.15	30%	36%

Gas Supply: $SF_6 - O_2$ with 38% O_2

Work Level	O_2 Consumption (l/min)	Injection Rate (l/Min)	RMV	Fi (Measured)	Fi (Calculated)
Rest	0.267	1.65	9.85	28%	28%
Moderate	0.841	8.2	21.31	29%	34%
Heavy	1.171	14.45	35.77	30%	35%

Subject: B. D. (Non-Diver)
Gas Supply: $N_2 - O_2$ with 43% O_2

Work Level	O_2 Consumption (l/min)	Injection Rate (l/Min)	RMV	Fi (Measured)	Fi (Calculated)
Rest	0.218	1.62	7.96	34%	36%
Moderate	0.719	8.5	23.69	36%	40%
Heavy	1.319	12.35	35.93	33%	39%

Gas Supply: $SF_6 - O_2$ with 38% O_2

Work Level	O_2 Consumption (l/min)	Injection Rate (l/Min)	RMV	Fi (Measured)	Fi (Calculated)
Rest	--	--	--	--	--
Moderate	0.977	8.6	21.06	31%	34%
Heavy	1.292	14.0	34.21	31%	35%

TABLE 3

Comparison of measured and calculated exhalation bag oxygen levels

MARK VIII

Subject: R. L. (Non-Diver)
Gas Supply: $N_2 - O_2$ with 43% O_2

Work Level	O_2 Consumption (1/Min)	Injection Rate (1/Min)	RMV	Fe (Measured)	Fe (Calculated)
Rest	0.266	1.8	9.31	30%	30%
Moderate	0.785	9.15	18.19	32%	32%
Heavy	1.493	13.15	41.08	30%	29%
Gas Supply: $SF_6 - O_2$ with 38% O_2					
Rest	0.162	1.35	5.52	23%	22%
Moderate	0.735	8.5	16.97	25%	25%
Heavy	1.308	14.3	33.22	25%	25%
Subject: W. L. (Diver) Gas Supply: $N_2 - O_2$ with 43% O_2					
Rest	0.365	1.36	7.12	22%	22%
Moderate	1.034	9.5	21.75	30%	30%
Heavy	1.965	14.9	35.78	28%	29%
Gas Supply: $SF_6 - O_2$ with 38% O_2					
Rest	0.225	2.0	4.46	25%	25%
Moderate	1.119	8.65	14.74	24%	23%
Heavy	1.636	15.6	19.26	25%	25%

TABLE 3

MARK XI

Subject: W. B. (Diver)
Gas Supply: $N_2 - O_2$ with 43% O_2

Work Level	O_2 Consumption (1/Min)	Injection Rate (1/Min)	RMV	Fe (Measured)	Fe (Calculated)
Rest	0.247	1.5	10.45	30%	29%
Moderate	0.716	6.65	25.75	29%	29%
Heavy	1.476	10.5	48.15	27%	27%
Gas Supply: $SF_6 - O_2$ with 38% O_2					
Rest	0.267	1.65	9.85	25%	25%
Moderate	0.841	8.2	21.31	25%	25%
Heavy	1.171	14.45	35.77	26%	26%
Subject: W. D. (Non-Diver) Gas Supply: $N_2 - O_2$ with 43% O_2					
Rest	0.218	1.62	7.96	31%	31%
Moderate	0.719	8.5	23.69	32%	33%
Heavy	1.319	12.35	35.93	29%	29%
Gas Supply: $SF_6 - O_2$ with 38% O_2					
Rest	--	--	--	--	--
Moderate	0.977	8.6	21.06	27%	26%
Heavy	1.292	14.0	34.21	26%	27%

TABLE 4

Volume of gas and oxygen lost from the system through the exhaust valve per minute and fraction of each breath lost through the exhaust valve.

MARK VIII

Subject: R. L. (Non-Diver)
Gas Supply: N_2 - O_2 with 43% O_2

Work Level	O_2 Consumption (1/Min)	Injection Rate (1/Min)	V_e (1/min)	V_o (1/min)	V_T (1)	f #/min	V_f (1)	V_f/V_T
Rest	0.265	1.8	1.53	0.46	1.59	5.85	0.26	0.16
Moderate	0.785	9.15	8.36	2.68	2.36	7.7	1.08	0.46
Heavy	1.493	13.15	11.66	3.49	2.19	18.8	0.62	0.28
Gas Supply: SF_6 - O_2 with 38% O_2								
Rest	0.162	1.35	1.19	0.27	1.1	5	0.24	0.22
Moderate	0.735	8.5	7.76	1.94	1.51	11.2	0.69	0.46
Heavy	1.308	14.3	13.0	3.25	1.67	20	0.65	0.39
Subject: W. L. (Diver) Gas Supply: N_2 - O_2 with 43% O_2								
Rest	0.365	1.36	1.00	0.22	1.42	5	0.20	0.14
Moderate	1.034	9.5	8.47	2.54	2.61	8.3	1.02	0.39
Heavy	1.965	14.9	12.94	3.63	2.86	12.4	1.04	0.36
Gas Supply: SF_6 - O_2 with 38% O_2								
Rest	0.225	2.0	1.78	0.445	1.78	2.5	0.71	0.40
Moderate	1.119	8.65	7.53	1.81	1.96	7.5	1.00	0.51
Heavy	1.636	15.6	13.96	3.49	1.76	10.8	1.29	0.73

TABLE 4

MARK XI

Subject: E. B. (Diver)
Gas Supply: $N_2 - O_2$ with 43% O_2

Work Level	O_2 Consumption (l/min)	Injection Rate (l/Min)	V_e (l/min)	V_o (l/min)	V_T (l)	F #/min	V_f (l)	V_f/V_T
Rest	0.247	1.5	1.25	0.38	0.587	17.8	0.07	0.12
Moderate	0.716	6.65	5.93	1.72	1.332	19.3	0.31	0.23
Heavy	1.476	10.5	9.02	2.44	1.660	29	0.31	0.19
Gas Supply: $SF_6 - O_2$ with 38% O_2								
Rest	0.267	1.65	1.38	0.34	0.535	18.4	0.075	0.14
Moderate	0.841	8.2	7.36	1.84	1.278	16.7	0.44	0.34
Heavy	1.171	14.45	13.28	3.45	2.077	17.2	0.77	0.37
Subject: B. D. (Non-Diver)								
Gas Supply: $N_2 - O_2$ with 43% O_2								
Rest	0.218	1.62	1.40	0.50	0.692	11.5	0.12	0.17
Moderate	0.719	8.5	7.78	2.49	1.316	18	0.43	0.33
Heavy	1.319	12.35	11.03	3.20	1.562	23	0.48	0.31
Gas Supply: $SF_6 - O_2$ with 38% O_2								
Rest	--	--	--	--	--	--	--	--
Moderate	0.977	8.6	7.62	2.06	0.903	23.3	0.33	0.37
Heavy	1.292	14.0	12.71	3.31	1.208	28.3	0.45	0.37

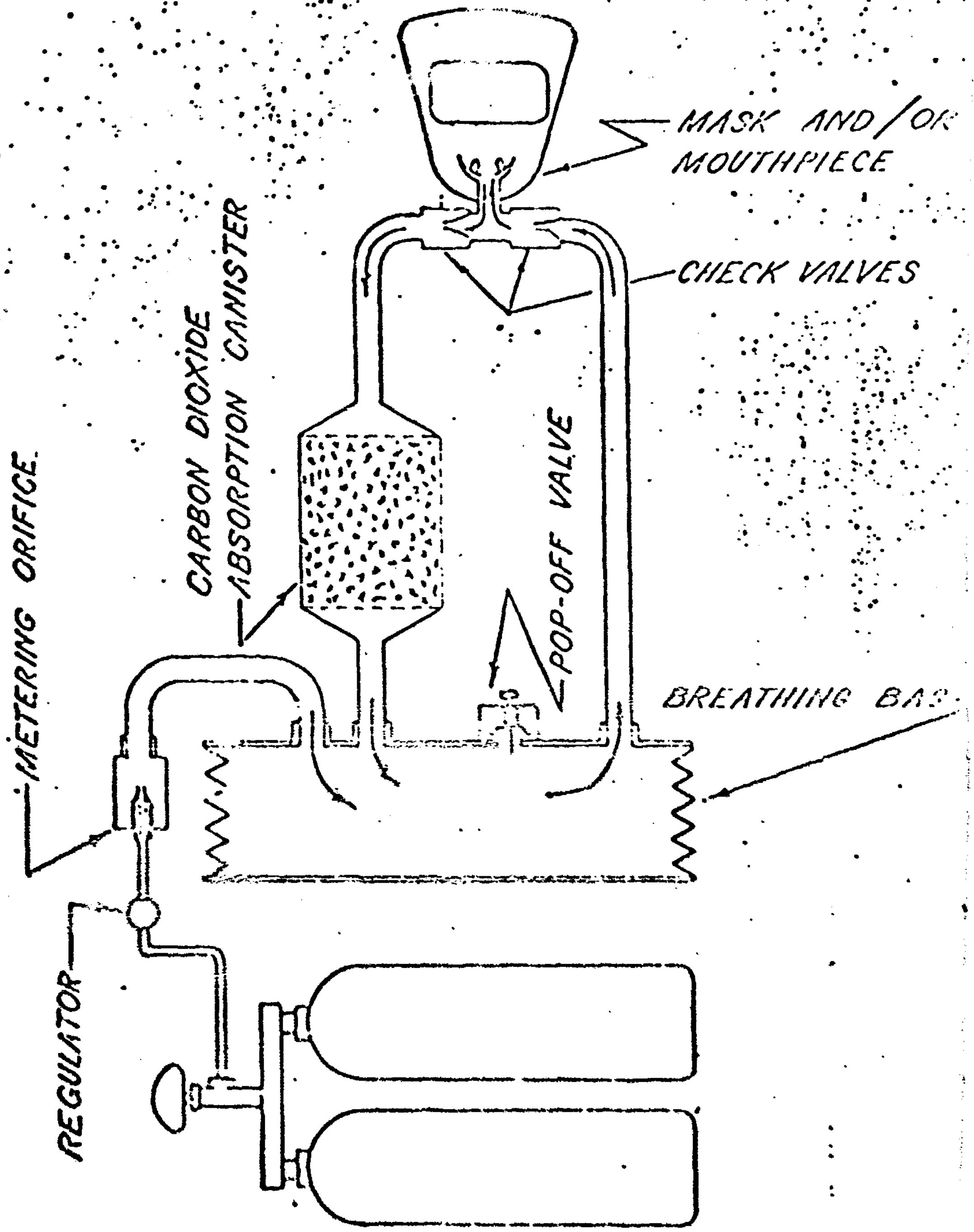

FIGURE I

Semi-closed circuit underwater breathing apparatus used in analysis

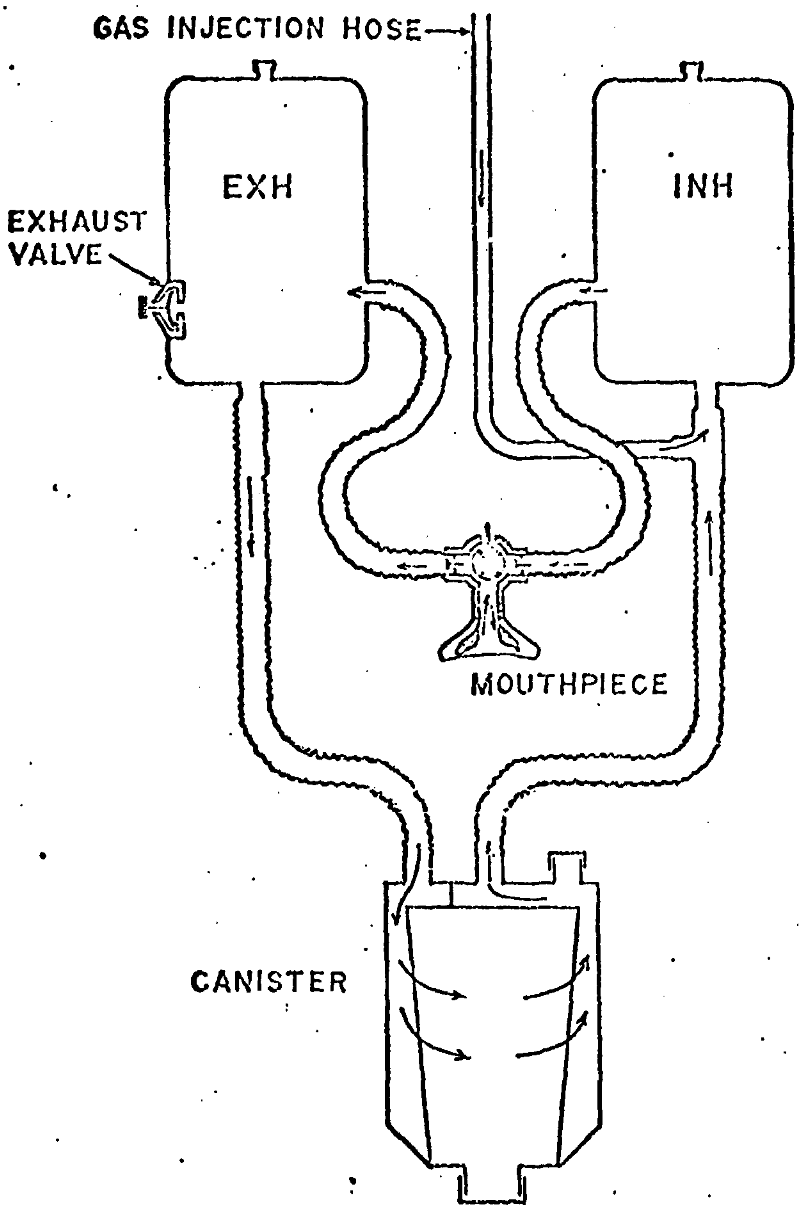

FIGURE II

Current model of semi-closed circuit underwater breathing apparat

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13. ABSTRACT

A diver breathing with an underwater breathing apparatus will have his ventilatory capability degraded by an inherent breathing impedance in the equipment used. The impedance of both the equipment and the diver's respiratory system will increase as ambient pressure increases. There is little informartion available concerning the deleterious physiological effects imposed on the diver breathing with an underwater breathing apparatus. A paucity of information delineating bioengineering specifications for breathing resistance in underwater breathhing apparatus exists. This study was undertaken to measure the breathing resistance enountered by an exercising subject using the U.S.Nawy Mark VIII ModI, ~~and Mark XI Mod0~~ semiclosed underwater breathing apparatus. Objectives of the study were: ~~a)~~ delineation of physiological effects imposed by equipment resistance in the presence of gasesLofnnormal and increased density; ~~b)~~ development of techniques to evaluate breathing resistance in diving equipment; ~~c)~~ tenative establishment of specifications for engineering design of diving equipment in terms of breathing resistance. All objectives of the study were attained.

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13. ABSTRACT

(continued) The ventilatory restrictions are discussed in terms of oxygen consumption, CO_2 production, heart rate, and work of breathing. Testing methods are proposed to determine breathing impedance in underwater breathing apparatus. Tenative standards for breathing resistance are proposed and discussed.

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